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GEOPHYSICAL EXPLORATION FOR STRATIGRAPHIC OIL TRAPS*

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ABSTRACT

Stratigraphic traps are defined and classified and the applicability of various geophysical methods for the discovery of each of the different types of stratigraphic traps is discussed. Some undeveloped techniques are suggested in this connection as subjects for research.

During the last few years a great deal of attention has been given to the so-called stratigraphic type of oil trap,[1] so that the advisability of conducting exploratory campaigns for the discovery of new oil and gas reservoirs of this type is now generally recognized. The amount of intelligent exploration with this objective, however, has been limited by the lack of any proved technique for its accomplishment. The writer hopes that by clarifying the objective and suggesting certain lines of research, he may contribute a certain impetus toward the development of such techniques. As the expression "stratigraphic trap" covers a great number of diverse geological conditions, until the geophysicist has all of these conditions clearly in mind he cannot fully utilize his imagination in devising geophysical methods for their discovery.

If we define simple stratigraphic traps as those in which the attitude of the reservoir bed is entirely monoclinal with no folding or faulting, such traps may be grouped into three categories, the lenticular type, the overlap type and the unconformity type. The lenticu-

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[1] *Stratigraphic Type Oil Fields—A Symposium*, A.A.P.G. Tulsa, 1941. Also see W. B. Wilson, *Classification of oil reservoirs*, A.A.P.G. Bulletin, Vol. 26, No. 7, p. 1291 (1942); H. R. Lovely, *Classification of oil reservoirs, ibid.*, Vol. 27, No. 2, p. 224 (1943); C. W. Sanders, *Stratigraphic type oil fields and proposed new classification of reservoir traps, ibid.*, Vol. 27, No. 4, p. 539 (1943); A. I. Levorsen, *Discovery Thinking, ibid.* Vol. 27, No. 7, p. 887 (1943).

lar type includes all those conditions involving porous beds or zones, limited in lateral extent in all directions, which lie entirely within the confines of one geological formation. Ancient sand bars and beaches involved in sediments of finer texture are the classic example of the lenticular type. As such bars and beaches are generally thin, however, and differ little from the immediately surrounding sediments in density, hardness, elasticity and other physical characteristics excepting only their permeability, they offer the least promise for discovery by geophysical techniques. Where saturated with salt water in their oil-free portions these reservoirs may be detected by electrical resistivity methods at very shallow depths, but because they are so thin they cannot be detected by such means at depths sufficient to yield the hydrostatic pressures required for efficient oil production. So-called "shoe string sands" include, in addition to old sand bars and beaches, various types of fossil sand-filled channels which for our purposes may be classified with the former. Such "shoe string sands" produce oil and gas in several petroleum provinces. The fields which they constitute, however, are scarcely large enough to justify extensive research into methods for discovering new ones of the same kind at this time.

Limestone reefs are similar in structure to bars and beaches, differing chiefly in the material of which they are formed. Many of them, however, are larger than the average sand bar. Due to that fact, and to the density and hardness of the limestone which composes them, they can in some cases be detected by seismic or gravimetric means.

Deltaic deposits and alluvial fans contain another sort of lenticular reservoir. The coarsest and most porous sediments in such structures are the foreset beds, which have several characteristics rendering them amenable to geophysical detection. These beds consistently have a slightly steeper dip than either the overlying or underlying strata; they have, in general, a directional divergence from the distributary axes of the deltaic structure, and as a result of the latter condition they commonly contain cross-bedding. Deltas and alluvial fans produce a considerable local thickening of the formation in which they occur, and the coarseness of the sediments in the foreset beds tends in some places to increase the specific gravity of the formation. A combination of these last two factors is competent to develop small positive gravity anomalies. The divergent and discordant dips of the foreset beds may be detected by seismic reflections; the thickening of the formation caused by the deltaic condition will often appear in the correlation of reflections; and contrasts in seismic velocities, noted when the foreset

zone is compared with overlying and underlying strata, may offer additional evidence of its existence. Very few oil-fields are generally conceded to be of deltaic origin, and the entrance of the action of a considerable amount of fresh water into the building of deltas and alluvial fans might be considered as militating against their value as petroleum reservoirs. It has been pointed out frequently, however, that considerable portions of the Gulf Coastal Plain sediments have the structural characteristics of a compound delta. The writer believes that many of the Gulf Coast oil fields which apparently lie on dip terraces without any evidence of actual anticlinal closure may be producing oil from the foreset zones of ancient deltas.

A third group of lenticular type traps may be characterized as permeable lenses. This term refers to lenses of high permeability grading off in all directions into more compact sediments. Such lenses are of common occurrence, but as they have no definite structural form like beaches, channels or reefs, no structural term is available to describe them. Their permeability may in some cases be due to original conditions of sedimentation, or it may be due to subsequent leaching by ground water. In still other cases permeable lenses may simply retain their original permeability while the pore space in surrounding rocks has been closed by cementation through the agency of ground water. Such permeable lenses occur both in clastic sediments and in limestones. They are particularly common in the eastern interior and Appalachian oil fields. They are necessarily difficult to discover by geophysical methods, but, as with ancient bars and beaches, some success in locating them with resistivity methods at very shallow depths has been reported.[2]

The second category of simple stratigraphic traps, which we have called the overlap type, is distinguished by the fact that the reservoir bed forms part of a series of beds which unconformably overlaps an older group of rocks. Therefore, in the overlap zone of the reservoir bed, the underlying strata will not conform to the reservoir bed but the latter will conform to the cover rock. In a simple overlap trap, accumulation occurs where a tongue of the overlapping reservoir rock extends up dip from the normal limit of deposition of that bed. Such tongues occur where, at the time of deposition, depressions or embayments existed in the surface upon which the reservoir bed was laid down. When, after deposition, the rock series containing the reservoir

[2] Joel Howard Swartz, *Oil prospecting in Kentucky by resistivity methods*, U. S. Bur. Mines, Tech. Paper 521 (1932).

of geophysical methods, the location of wildcat wells on suspected stratigraphic traps can be so controlled as to increase greatly the chances of discovering oil deposits. One example will suffice. Let us assume that an oil accumulation extends for several miles along the up dip edge of a reservoir bed and is crossed by one or more plunging anticlinal and synclinal axes. It is obvious that the productive belt will be considerably wider along the anticlinal axes than along the synclinal axes. Therefore, other things being equal, greatest latitude for the location of an exploratory well will be had on the most prominent anticlinal axes, and the risk of missing the oil deposit completely will be least in a well so located.

Where there is sufficient control available from surface geology and well logs, it may be possible to locate the edge of a reservoir bed entirely without the aid of any geophysical method. However, even in such cases, electrical well logs for correlation purposes generally prove very useful, and the use of various geophysical methods for determining modifying structural features is always advisable to determine the best location for test wells. Of these methods the reflection seismograph is most commonly used and is admittedly the best means of working out structural details where conditions permit its application. In certain cases, however, other methods may be more effective.

Aside from the actual pinch-out of the reservoir bed, itself, faults and anticlinal noses are usually the principal factors in localizing the accumulation of petroleum in complex stratigraphic traps. In many areas the lack of persistent reflecting horizons makes correlation of seismic reflections impractical and this constitutes a considerable handicap to the location of faults with the reflection seismograph. If the faults are not limited to the deeper beds only, but continue upward to the surface, they may be mapped by surface geological methods if recognizable outcrops are plentiful. But in a large part of the oil-producing regions of the world the bedrock is buried under alluvium or glacial drift, or it consists of unconsolidated formations which lose, when they are weathered, what few distinguishing characteristics they have. Therefore any geophysical method, even though its penetration be very shallow, can be used to advantage if it is able to detect distinguishing characteristics of the immediate subsoil formations. In this way geophysics is employed essentially as a tool of surface geology. Such procedure is common in mineral exploration, but has been seriously neglected by petroleum geophysicists.

Both faults and anticlinal noses can in many cases be located by

tracing the subsoil outcrop of certain strata geophysically. Most sediments contain certain strata having a greater magnetic permeability than the contiguous strata, and the subsoil outcrop of such strata can be traced with the magnetometer. Certain beds have a definitely higher seismic velocity than contiguous beds, and their subsurface outcrop can be traced with short, rapid refraction profiles. Still other beds will have a large or small electrical resistivity, or a high or low specific gravity, and their subsoil outcrops can consequently be traced with electrical or gravimetric instruments. The trace of such beds will swing down the regional dip in a large curve as a plunging anticlinical nose is crossed, and will swing through a curve up the dip as a plunging synclinal trough is crossed. More abrupt curvature of the trace indicates a fault, and if the fault has great displacement a complete discontinuity may be found. It is true that these methods have the disadvantage of not outlining with any precision the geological structure at or near the level of the oil producing horizons; but the methods are cheap to operate and certainly definite surface geology is better than questionable subsurface information or none at all.

In certain exceptional regions where the crystalline rocks of the basement complex occur at a few thousand feet or less, anticlinal folds and faults can be located with a magnetometer or gravimeter because of the way in which these structures deform the surface of the crystalline rocks and the consequent effect of such deformation on the magnetic or gravitational field at the earths' surface. This of course, is a common application of these instruments in petroleum prospecting. Although the areas are limited in which such application can be made, it is better suited to prospecting for complex stratigraphic traps than for true structural closure, because the crystalline core of an anticlinal nose or, what is very similar, a buried crystalline ridge, or even a long, tilted fault block in the crystalline basement, has a much greater effect on the magnetic or gravitational field at the earth's surface than does the small uplifted crystalline mass in the core of the usual, relatively small closed anticline.

The determination of the pinching out of certain reservoir formations is a more difficult task for the geophysicist. The thinning of limestone reefs has a definite effect on the gravity field, but, unfortunately, in West Texas and New Mexico where a large number of gravimetric surveys in search of reef type oil fields have been made, the gravity field is complicated by prominences in the crystalline basement, the reefs being genetically related to those prominences. Where

sufficiently shallow, such reefs can also be outlined in some cases by seismic refraction methods.

Where the stratigraphic thinning of a reservoir formation is due to the system's overlapping unconformably upon an older system of rocks, such as a basement complex or a much more consolidated mass of sediments, gravity surveys may indicate to a very close approximation the degree of thinning in the younger rock system. If the younger group of strata is not too thick, seismic refraction surveys may serve to measure the diminution in their thickness with a much greater degree of accuracy than gravimeter measurements. In some instances it is possible to determine the thinning of a sedimentary system over a high velocity basement by means of seismic reflections, but in many other cases it is difficult if not impossible to isolate the top of high velocity crystalline rocks among the reflections obtained.[3]

The geophysical methods just discussed are special methods applicable to peculiar cases. They should not be underemphasized, because they will no doubt lead to the discovery of many oil fields where properly applied. In general, however, the most obvious and most useful method for the localization of stratigraphic thinning is the reflection seismograph survey, which lends itself most readily to the construction of isopach maps. By building vertical cross-sections tracing the more prominent reflections along lines at right angles to the regional strike, and by contouring in ground plan the interval between prominent correlatable reflections or between convergent phantom horizons, the approximate position of the up dip edge of a reservoir bed lying within any of the isopached intervals can be estimated. The exact position of the reservoir beds in the geological section naturally must be determined from well logs or outcrops, and it is apparent that having a large number of well logs within the area being worked will greatly increase the accuracy of the method.

It is, of course, desirable to map the isopachous intervals between reflections which can be correlated over long distances. The method requires covering large areas, and in some cases the cost of continuous

[3] This seems rather surprising, since the greatest velocity discontinuity in the section might be thought to occur generally at the top of such a basement mass. One explanation of the phenomenon is that because of the probable magnitude of the velocity contrast between the basement rocks and the overlying sediments, reverberations take place between the basement and the earth's surface and between the basement and other good reflecting surfaces, these reverberations arriving on the record at a later time than the simple basement reflection, and thus serving to mask what has been thought might be its most distinguishing character, namely, that it ought to be the last arriving persistent simple reflection.

coverage may therefore be considered prohibitive. Unfortunately, there are a large number of regions where "spot correlation" is entirely unreliable. In such areas, if there is not too much irregularity in the topography or the weathering, and if reasonably good records are otherwise obtained, interrupted dip shooting may be used to lessen the cost of the survey as compared with continuous profiling. In order to use interrupted dip shooting (commonly called "leap-frog" shooting) to trace the convergence of phantom horizons, it is necessary that there exist one or more readily apparent planes of convergence in the cross sections. In some localities these planes can be correlated over great distances. By planes of convergence we mean horizons toward which either the overlying or the underlying reflections, or both, converge. If such planes are not sufficiently definite to be correlatable over considerable distances, the danger exists that phantom horizons may be traced across undetected faults and the intervals between such phantom horizons will thus be in error.

In order partially to obviate this danger it is at present necessary in a large number of areas to use so-called continuous coverage. While such continuous coverage greatly enhances the accuracy of a reflection survey when used discreetly, it can also be a source of gross error when used carelessly. In territory where all reflection records are good, one can correlate each reflection almost automatically from the record made over one spread to the record made over the contiguous spread. But where some of the records are poor, as is generally the case, the average field seismologist has a tendency to carry a reflection through the nearest corresponding cycle on the next adjacent record and through the adjacent traces on the same record without observing whether there is any change in reflection character, or even without making sure that he is still working with a true reflection. Since poor reflections are most likely to occur where a profile crosses a fault, if continuous profiles are subject to this careless, but all-too-common type of interpretation, they may be even more dangerous than interrupted dip shooting; for in picking dips on non-continuous records almost every seismologist will at least make sure that he is picking the dips on real reflections. Many errors made in the interpretation of continuous profiles could be avoided if the interpreter would systematically review his interpretations, attempting to correlate from one good reflection to the next, skipping over all intervening doubtful records and using the character of the reflection and the time intervals between good reflections as his criteria.

Both to avoid the errors inherent in any of these methods of seismic

reflection interpretation, and to permit correlation of reflections or groups of reflections between areas considerable distances apart, new criteria are needed. Such long distance correlations would be especially beneficial in making isopach studies for the localization of stratigraphic traps.

One of the principal characteristics which has been used for many years for the correlation of reflections is their amplitude. Automatic volume controls now incorporated into many reflection seismographs, however, so suppress the amplitude as to make it a poor characteristic for correlation purposes, and even the best automatic volume controls vitiate this criterion to some extent. It therefore seems that some advantage might be obtained by retaining on a composite trace the relative amplitudes of the incoming reflections and at the same time controlling the amplitudes of the traces used for distinguishing other characteristics of the reflection. It has even been suggested[4] that by recording the gradual decrease in the amplitude of the reflections produced by a bed, the thinning of the bed might be mapped. This proposal would be difficult to test with modern instruments unless modified somewhat as suggested.

Another method of long distance correlation, which has already revealed some merit, is the analysis of the frequencies present in different reflections. This can be accomplished instrumentally in various ways.[5] While in general the frequencies composing a reflection decrease with the increasing depth of the beds which produce them, reflecting horizons exist which produce higher frequency reflections than overlying horizons, or conversely, which produce lower frequency reflections than underlying horizons. This characteristic has been observed to continue over considerable distances. In several cases[6] a careful analysis of reflection frequencies has shown that while the frequency of each individual reflection on the records decreases as its arrival time increases, the relative frequencies of the reflections as compared to each other remain in the same order, which in the cases analyzed was not entirely the order of decreasing frequency with increasing arrival time. Such analyses of frequencies made for successive areas might supply valuable data for the long distance correlation of reflections and facilitate the construction of reflection isopach maps.

One further suggestion is that correlation of seismic horizons over

[4] Bela Hubbard: Personal communication.

[5] Joseph L. Adler: *United States Patent No. 2279191.*

[6] A. P. Crary: Unpublished report.

long distances may be accomplished on the basis of their respective velocities. In certain regions when the interval velocity logs obtained from shooting different wells are compared, they can be correlated much as electrical logs are correlated. While the interval velocity of a given formation will not be the same in all wells, the relative interval velocities of successive formations will form similar patterns. It is therefore suggested that the interval velocity or seismic acceleration curves obtained by comparing the arrival time with the time increment across a spread for all the reflections on a large number of records in one area, when compared with the same type of curve made for another area, might yield another basis for long distance seismic correlation in some cases. Such curves would, of course, be useful for this purpose largely in areas where reflecting horizons are numerous throughout the stratigraphic section, and where there are a reasonable number of sharp changes in interval velocity, both increases and decreases as the depth becomes greater. Where the problem involved in the search for stratigraphic traps, however, is to trace through some region a definite disconformity in the strata accompanied by a marked velocity change, such interval velocity curves may prove useful even though only the one velocity discontinuity exists.

In this presentation it has been assumed that in any region to be explored there is sufficient information available on its geology for one to know in advance what types of stratigraphic traps may be expected. It is doubtful, however, if any oil field could be found which would conform exactly to any of the types of traps herein described. The types may be better considered as determining distinct factors, one or more of which may be involved in any stratigraphic oil trap. Therefore, discovery of stratigraphic oil fields is most likely to result from a coordinated regional geological and geophysical survey combining all appropriate geophysical methods, the results of which are analyzed by a competent geologist with courage and imagination.

GEOPHYSICAL HISTORY OF THE IOWA FIELD, CALCASIEU AND JEFFERSON DAVIS PARISHES, LOUISIANA*

J. BRIAN EBY†

ABSTRACT

The discovery well of the Iowa field was drilled in October of 1931, and the field has produced 48,000,000 barrels of oil to date. The history of the early refraction seismograph, gravity, and reflection seismograph exploration of this important field is presented.

The Iowa Field, Calcasieu and Jefferson Davis Parishes, Louisiana, is one of the most important oil fields within the state and its geophysical history is one of the outstanding examples of the success of early seismograph and torsion balance investigations. Since up to the present time salt has never been encountered in any wells of the field, the structure is classified as a deep-seated salt dome structure. The oil accumulations occur in sands that are arched over the top of the dome. Considering the size and importance of the Iowa oil field, very little geological and geophysical information has yet been released concerning it.

One of the earliest references to the discovery of Iowa is found in the American Association of Petroleum Geologists Bulletin, Volume 16, pages 255–256, March 1932, by L. P. Teas, in which he calls attention to the fact that surface gas seeps had interested Lee Hager in the area as early as 1916. These gas seeps occurred in Bayou Arceneaux (Fig. 1) and on the strength of them, in 1923, the Gulf drilled a well to 3381 feet, near the center of Section 36, Township 8 South, Range 7 West; the Union Sulphur Company, in 1926, following refraction work in the vicinity of the Gulf well, drilled two additional holes, one to 2234 feet, and one to 4850 feet, both being dry holes, but showing some shallow gas. These two wells, as in the case of the Gulf well, were from 2 to 2½ miles north of the present field.

In the early part of the summer of 1929, the Vacuum Oil Company, in view of the surface gas seeps above-mentioned, and the occurrence of gas in the Union Sulphur Company shallow wells, again took up leases in this territory for further geophysical investigations, with the

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The author acknowledges with appreciation the courtesy of the Shell Petroleum Corporation in releasing much of the early Iowa data used in this paper. He is likewise grateful to Mr. Henry Cortes for cooperation in preparing and editing the manuscript.

south line of their block occurring two miles south of the township line between Township 8 South and Township 9 South.

The first positive geophysical indications of the deep-seated Iowa structure were found by a refraction seismograph crew of the Shell Oil Company, in June 1929. The picture obtained by this early refraction investigation is indicated by the seismograph map, Fig. 1.

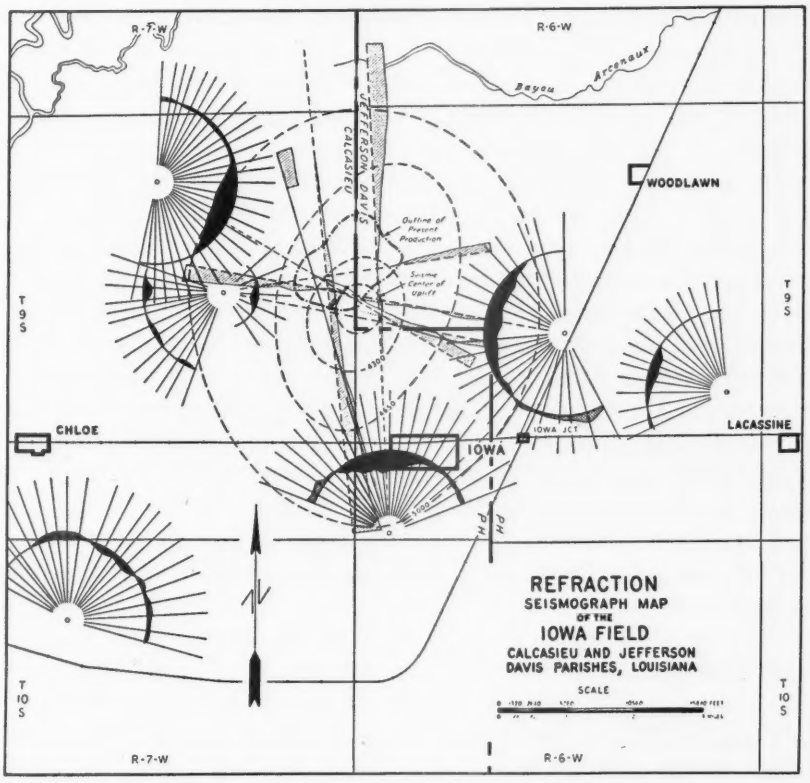

FIG. 1. Refraction seismograph map of the Iowa Field, Calcasieu and Jefferson Davis Parishes, Louisiana. Dot-dash line is outline of present production, dashed lines seismic contours. Refraction accelerations are solid black, retardations criss-crossed. On profiles across the prospect, accelerations are cross-hatched. Maximum acceleration for the northwestern-most shot point is 14/100 second.

In examining this map, it will be seen that the outline of present production, the dot-and-dash line, lies slightly north of the center as indicated at that time. The seismograph contours, representing a closure of a little more than 700 feet at a depth of 5000 feet, are based on

what the seismologists call a 9000 ft. per second speed layer. No salt velocities, namely, 14,000 to 15,000 ft. per second, were found. The average length of the refraction shots was from five to six miles.

The locations of all important shot points are indicated on Fig. 1, and the accelerations found on each ray are plotted from the arbitrary arc back toward the direction of the shot point. Retardations are plotted before the arc and in the direction of the observation station. The map indicates accelerations in a solid black pattern and retardations in a criss-cross pattern. Several profile lines were shot across the dome as indicated and observed accelerations are plotted in the single cross-hatch. On the original plates, the scale of the acceleration diagrams is one millimeter equals one-hundredth of a second; however, Fig. 1 has been considerably reduced for publication. In order that the reader can tell the exact accelerations obtained from Fig. 1, the maximum acceleration indicated for the northwestern-most shot point is 14/100 of a second. This was the maximum acceleration obtained in any direction over the uplift. It will be noted that the same high acceleration was found on the shot point immediately south of the structure and lesser accelerations were found from the east side of the structure. The discovery of the Iowa structure by refraction seismograph marks one of the early examples of a deep dome being correctly located without obtaining salt velocities. Up to the present time no salt has been found down to the depth penetrated by the deepest well, this being Shell's #19 Heyd, which was drilled to a total depth of 9161 feet.

During the summer of 1929, Vacuum Oil Company (Magnolia) was carrying out extensive torsion balance investigations in their block of leases and definitely reported a deep-seated dome in August of that year. Two torsion balance maps, based on Shell gravity work, Figs. 2 and 3, indicate the gravity picture obtained during the latter half of 1929 and early 1930. Fig. 2 is a torsion balance map showing the averages of observed gradients, and Fig. 3 shows average gradients corrected for regional east-west gradients. Isogal lines are indicated on Fig. 3 and the outline of present production is also indicated on both Figs.

Dr. W. P. Jenny, in the *Oil and Gas Journal* for July 14, 1932, published a brief account of the Iowa gravity picture under the heading of "Geophysical Prospecting in the Gulf Coast Had to Overcome Many Difficulties." This article included a small gravity map of the Iowa Field.

In considering the early gravity work at Iowa, it was presumed that a salt dome existed at such depth and of sufficiently small magnitude to be in part overshadowed by the larger effect of the Welch dome. Accordingly, the observed gradients at Iowa were corrected

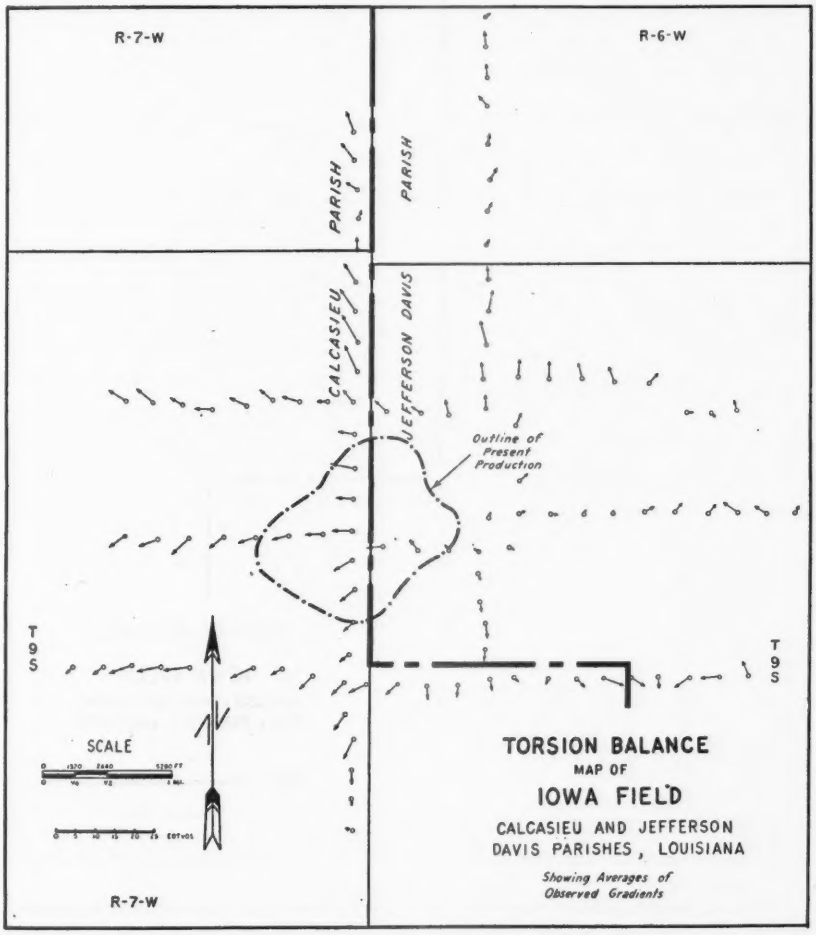

FIG. 2. Torsion balance map of the Iowa Field, showing averages of the observed gradients. The outline of present production is shown as dot-dash line.

for this effect by subtracting an east-west component. The top of the gravimetrically indicated structure thus obtained coincided quite accurately with the top of the structure as later developed by drilling.

Three examples of the early use of the reflection seismograph in

outlining a deep-seated structure are given by Figs. 4, 5 and 6. All three pictures refer to the Iowa Field and represent work by two different and independent crews. Fig. 4 represents a very detailed reflection

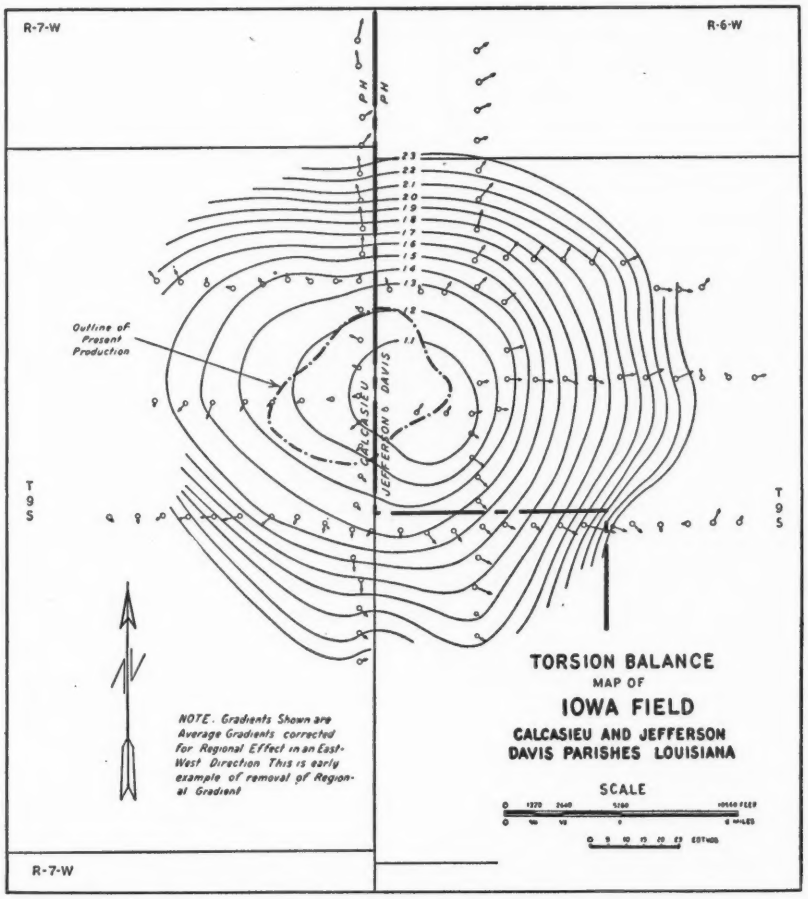

FIG. 3. Torsion balance map of the Iowa Field, showing average gradients corrected for east-west regional gradient—an early example of regional removal. The outline of present production is shown as a dot-dash line, and the isogal contours as solid lines. The contour interval is 0.1 mgl.

picture made for the Vacuum Oil Company by Geophysical Research Corporation during the months of July and August, 1929, and is an exceptionally fine example of the early use of this method in outlining and detailing deep-seated structures. This reflection picture was car-

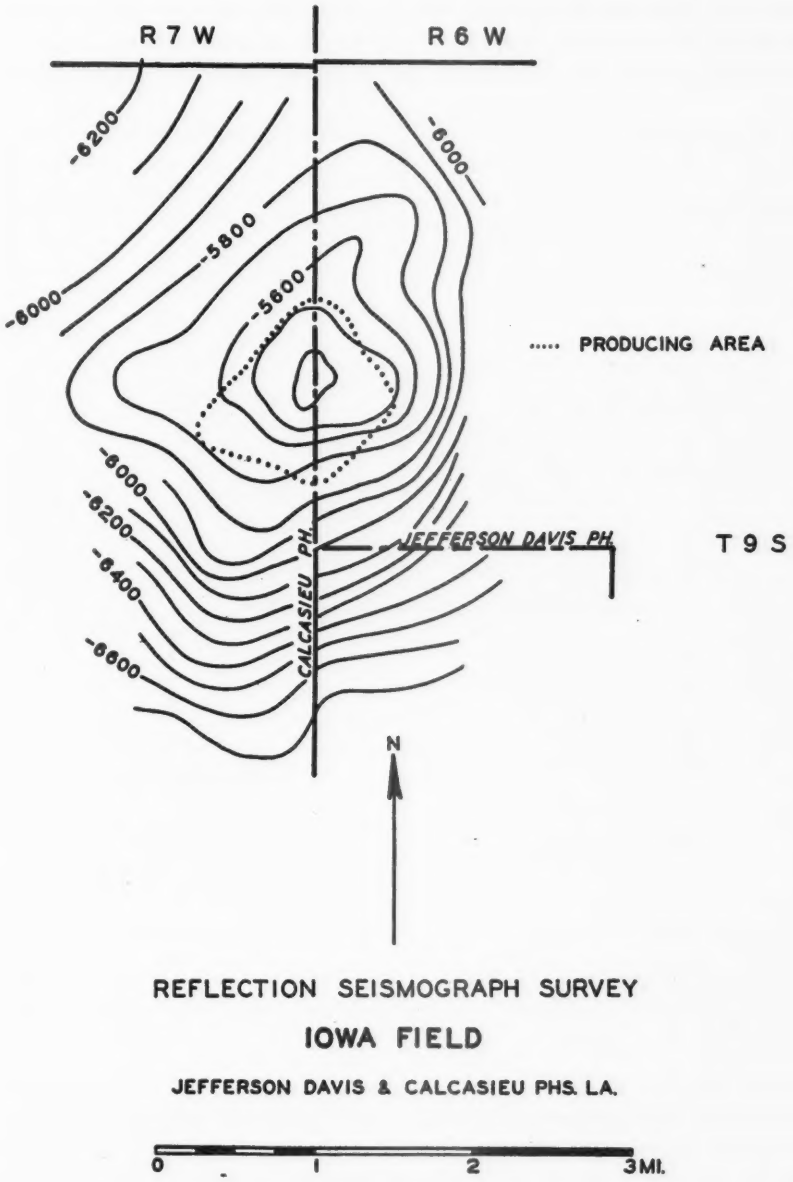

FIG. 4. Detailed reflection seismograph survey of the Iowa prospect made in 1929. Dotted line shows outline of present production, solid lines seismic contours. The contour interval is 100 feet.

ried out prior to the location of the discovery well of the oil field, Vacuum Oil Company's B. T. Waite #1, in October of 1931. Figs. 5 and 6 represent two interpretations made by Shell Oil Company of

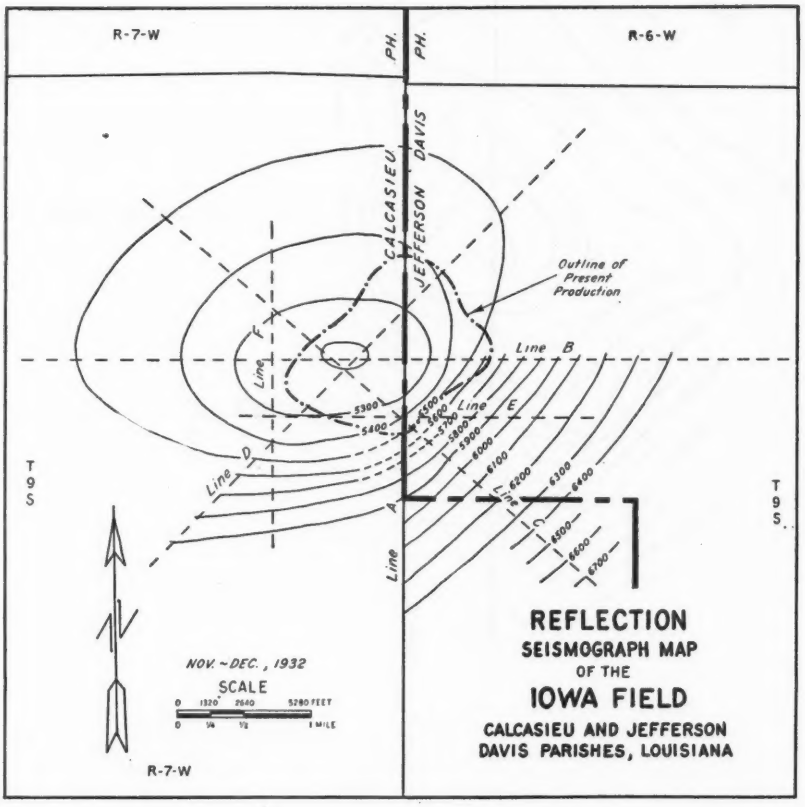

FIG. 5. Reflection seismograph map of Iowa Field, based on 1932 data. Dot-dash line shows outline of present production, solid lines seismic contours. Contour interval is 100 feet.

data observed during the latter part of 1932. Fig. 5 presents a conventional interpretation assuming no horizontal velocity gradient, whereas Fig. 6, an interpretation dated February 1933, shows the effect of introducing a correction for lateral velocity gradient; it will be seen that in making this correction a very close approximation to the structure, as now developed, was found at that time.

The Iowa Field is a low relief structure, more or less circular in out-

line and embracing nearly a thousand producing acres. There are two Miocene sands, one at 4400 feet and one at 5200 feet; and three Oligocene sands, one at 6600 feet, one at 7000 feet and one at 8200 feet.

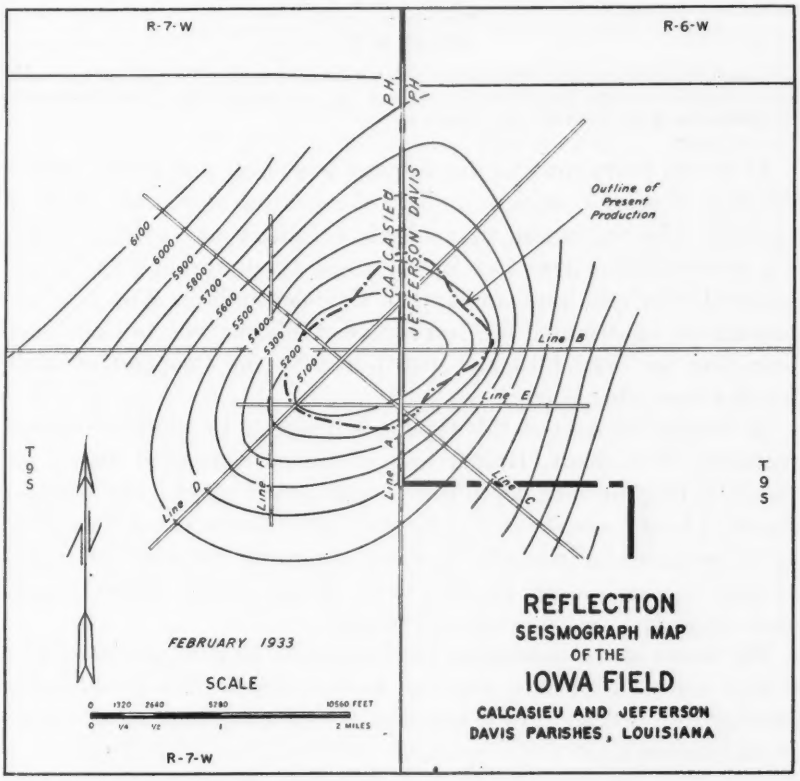

FIG. 6. A 1933 interpretation of the 1932 reflection seismograph map of the Iowa Field, in which a correction was introduced for the effect of lateral velocity gradient. Dot-dash line shows outline of present production, solid lines are the seismic contours at a 100 foot contour interval.

Structural closure on the 7000-ft. sand appears not to exceed 250 feet, which, as can be seen from Fig. 1, is considerably less than that indicated by the earliest refraction shooting.

The Iowa Field has already produced in excess of 48,000,000 barrels of oil, ranking it one of the most highly important oil fields in the Gulf Coast region. The detail of its geophysical discovery deserves to become a matter of record.

LEAST SQUARES DETERMINATION OF THE VELOCITY FUNCTION $V=V_0+kz$ FOR ANY SET OF TIME DEPTH DATA*

J. A. LEGGE, JR.† AND J. J. RUPNIK†

ABSTRACT

A method is presented by means of which a least square fit of the circular ray path plotting function to time-depth data is obtained. An example is worked out illustrating the application of the method to an actual case.

In recent years considerable interest has developed in the lateral variation of seismic velocity and in the control of seismic plotting functions. The realization that seismic velocities may vary laterally to a considerable extent has mainly come about through the availability of relatively large amounts of time-depth data. Well velocity shooting has contributed the best source of information. In California these data are assembled and distributed by the Cooperative Well Velocity Surveying Group.

In comparing data of this type it is desirable to apply a uniform treatment throughout. Hafner[1] has described a method based on visually fitting the time depth points to standard curves. The method presented here is one developed by the United Geophysical Company for the purpose of eliminating as much as possible the personal factor involved in visual fitting, in order to obtain as nearly a uniform treatment of the data as conditions will permit.

By means of the method to be described a least square fit of the circular ray path plotting function to time-depth data is obtained. This function is based on the assumption of a linear increase of velocity with depth, *i.e.*,

$$V = V_0 + kz \tag{1}$$

where V = seismic velocity at depth z
V_0 = seismic velocity at the datum
k = rate of increase of velocity.

It can also be shown that the depth z is given by

$$z = (V_0/k)(e^{kt} - 1) \tag{2}$$

* Presented at the annual meeting, Fort Worth, Texas, April, 1943.

† United Geophysical Company, Pasadena, California.

[1] W. Hafner, *The seismic velocity distribution in the Tertiary basins of California*, Seis. Soc. of Am. Bull., Vol. 30, No. 4, October, 1940.

in which t is the one-way time. The derivation of this function and its characteristics have been described by Slotnick.[2]

In order that a least square fit to Eq. 2 be obtained the parameters V_0 and k must satisfy the condition that:

$$\Delta = \Sigma[z - (V_0/k)(e^{kt} - 1)]^2 \text{ be a minimum.} \tag{3}$$

This relation requires that the derivative of Δ with respect to the parameters equal zero. The process of taking the derivatives may be simplified somewhat by considering the ratio V_0/k as a single parameter. $\partial\Delta/\partial(V_0/k)$ and $\partial\Delta/\partial k$ are therefore:

$$\frac{\partial\Delta}{\partial(V_0/k)} = -2[\Sigma z(e^{kt} - 1) - (V_0/k)\Sigma(e^{kt} - 1)^2] \tag{4}$$

$$\frac{\partial\Delta}{\partial k} = -2(V_0/k)[\Sigma zte^{kt} - (V_0/k)\Sigma te^{kt}(e^{kt} - 1)]. \tag{5}$$

V_0/k may be eliminated between these equations by substituting

$$V_0/k = \Sigma z(e^{kt} - 1)/\Sigma(e^{kt} - 1)^2 \tag{6}$$

from Eq. 4 into Eq. 5, giving:

$$\frac{\partial\Delta}{\partial k} = -2\frac{\Sigma z(e^{kt} - 1)}{\Sigma(e^{kt} - 1)^2}\left[\Sigma zte^{kt} - \frac{\Sigma z(e^{kt} - 1)}{\Sigma(e^{kt} - 1)^2}\Sigma te^{kt}(e^{kt} - 1)\right]. \tag{7}$$

The transcendental nature of this relation prevents the isolation of k. Hence, it is necessary to utilize a graphical method for the solution. This is accomplished by plotting values of $\partial\Delta/\partial k$ which correspond to several arbitrary values of k, as in Fig. 1 (a). From the curve thus defined the value of k may be read such that $\partial\Delta/\partial k = 0$. V_0 is similarly obtained from a plot of the V_0's. A value of V_0 for each of the arbitrary k's can be obtained from Eq. (6). Thus, with both the parameters determined, the solution is complete.

A measure of the quality of the fit is desirable and can be obtained from the standard deviation

$$\sigma = (\Delta/n)^{1/2} \tag{8}$$

in which Δ is given in Eq. (3) and n is the number of the depth points. The computation of σ is considerably simplified by substituting Eq.

[2] M. M. Slotnick, *On seismic computations, with applications, II*, GEOPHYSICS, Vol. I, No. 3, October 1936.

3 in 8 and squaring as indicated:

$$\sigma=\left[\left\{\Sigma z^2-2(V_0/k)\,\Sigma z(e^{kt}-1)+(V_0/k)^2\,\Sigma\,(e^{kt}-1)^2\right\}/n\right]^{1/2}. \quad (9)$$

With the exception of Σz^2 the summations under the radical have previously been computed in the process of obtaining the least square fit.

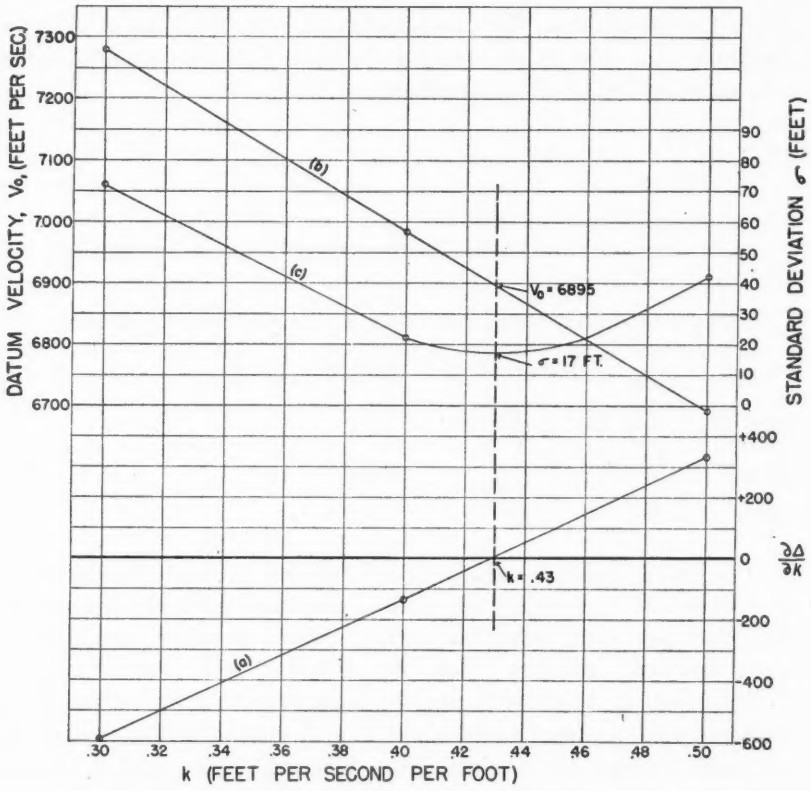

FIG. 1. Example of the computation of the constants in $V=V_0+kz$ for a well in Kern County, California. Curve (a) is $\partial\Delta/\partial k$ as a function of k, used to determine k for best fit. Curve (b) is a plot of V_0 as a function of k, used to determine the value of V_0 corresponding to the best-fit value of k. Curve (c) for σ has a minimum at the best-fit value of k.

In view of the fact that the procedure is more or less that of trial and error it is advantageous to have a rough idea of the value of k before the calculation is begun. The arbitrary values of the parameter k can then be selected such that their range includes the solution. The

estimation of k can be accomplished either on the basis of previous information which may be available in the area, or by comparing the time depth points with standard curves as described by Hafner.[3] It is seldom necessary to compute more than three values of $\partial\Delta/\partial k$ when the approximate value of k is known.

TABLE I

ILLUSTRATION OF THE CALCULATION OF THE CONSTANTS IN $V=V_0+kz$ FOR A WELL IN KERN COUNTY, CALIFORNIA

z	t	$e^{.3t}-1$	$te^{.3t}$	$e^{.4t}-1$	$te^{.4t}$	$e^{.5t}-1$	$te^{.5t}$
1400	.198	.06120	.21012	.08242	.21432	.10407	.21861
2400	.322	.10142	.35466	.13746	.36626	.17468	.37825
3400	.447	.14351	.51115	.19578	.53451	.25045	.55895
4400	.564	.18436	.66798	.25307	.70673	.32578	.74774
5400	.678	.22556	.83093	.31154	.88922	.40354	.95160
6400	.779	.26327	.98408	.36561	1.06381	.47624	1.14999
7400	.881	.30252	1.14752	.42248	1.25320	.55348	1.36862
8400	.981	.34219	1.31668	.48053	1.45240	.63313	1.60210
① $\Sigma z(e^{kt}-1)$			9644.20		13,409.5		17,491.0
② $\Sigma(e^{kt}-1)^2$			.397416		.768189		1.30704
③ Σzte^{kt}			36,159.3		39,190.0		42,488.3
④ $\Sigma te^{kt}(e^{kt}-1)$			1.48954		2.24485		3.17593
⑤ $V_0/k=①/②$			24,267.3		17,456.0		13,382.1
⑥ $(V_0/k)^2=⑤^2$			588.902×10^6		304.712×10^6		179.081×10^6
⑦ $2V_0/k=2\cdot⑤$			48,534.6		34,912.0		26,764.2
⑧ $V_0=k\cdot⑤$			7280.19		6982.40		6691.05
⑨ $V_0/k\cdot④$			36,147.1		39,186.1		42,500.6
⑩ ③−⑨			+12.2		+3.9		−12.3
⑪ $\partial\Delta/\partial k=-⑦\cdot⑩$			-592×10^3		-136×10^3		$+329\times10^3$
⑫ Σz^2			234.08×10^6		234.08×10^6		234.08×10^6
⑬ $\sigma^2=\frac{⑫-⑦\cdot①+⑥\cdot②}{n}$			5211		493		1799
⑭ $\sigma=(⑬)^{1/2}$			72		22		42

In the absence of any information on which to base an estimate of k, the sign of $\partial\Delta/\partial k$ can be utilized to locate the solution. If, for example, $\partial\Delta/\partial k$ is negative for a k of 0.5 the solution is greater. If $\partial\Delta/\partial k$ is then determined for 0.7 and is found to be positive it is apparent that the value of k such that $\partial\Delta/\partial k=0$ is between 0.5 and 0.7. In cases of this type it may be necessary to calculate several test values to cover the solution. Experience has shown that if very many time depth data are to be fitted the standard curves referred to above are well worth the time and effort spent in constructing them.

An example is presented to illustrate the application of the method to an actual case. Fig. 2 shows the time-depth curve of a well in Kern

[3] Hafner, *loc. cit.*

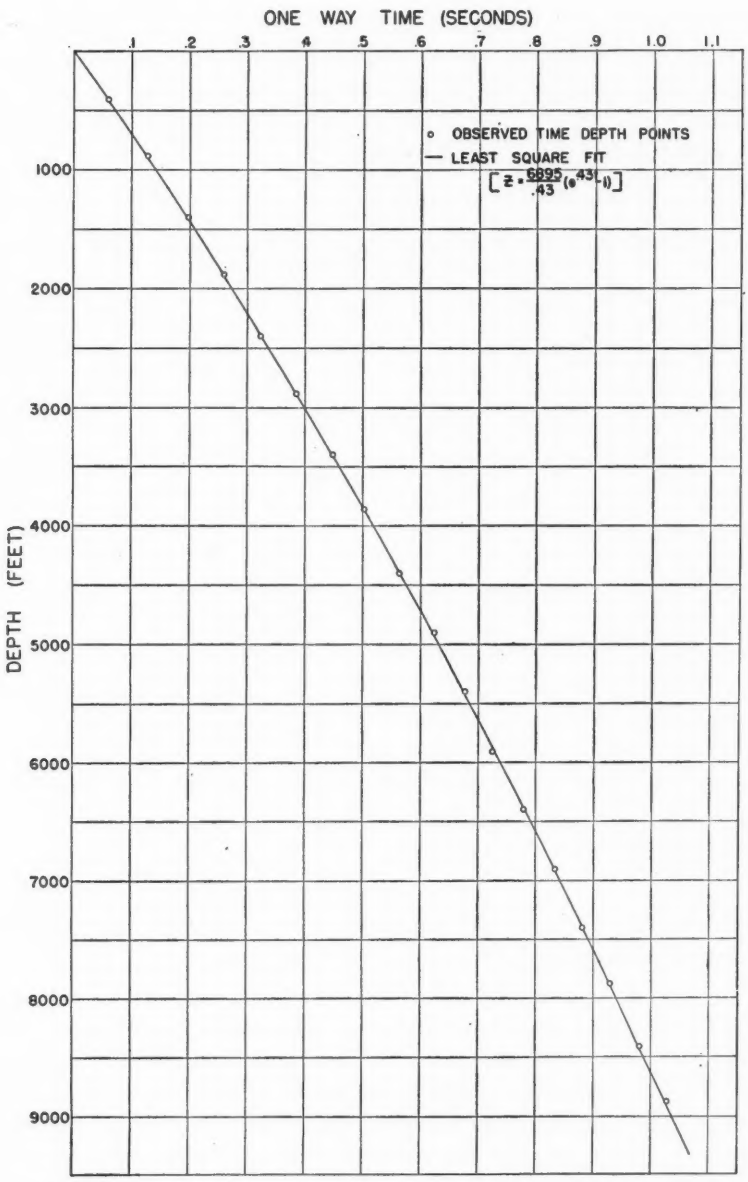

FIG. 2. Observed time-depth points, and best linear velocity assumption time-depth curve fitted to them, for a well in Kern County, California. Standard deviation of curve from observations is $\sigma = 17$ feet.

County, California. The time-depth points as well as the least square fit are shown.

Well velocity surveys are usually made in 500 foot intervals. If the time-depth curve is relatively smooth it has been found that no appreciable loss in accuracy is incurred by limiting the data to eight or ten evenly distributed points. In the example the fit was made to points at 1000 foot intervals beginning with 1400 feet.

A comparison of the time-depth data with standard curves indicated that k was approximately 0.4. $\partial\Delta/\partial k$ was then computed for 0.3, 0.4, and 0.5 as shown on the calculation sheet, Table I, and the results plotted in Fig. 1, (a). Similarly V_0 and σ were determined for these values of k and plotted as indicated in Fig. 1, (b) and (c). It is noted that when $\partial\Delta/\partial k=0$, $k=0.43$. Correspondingly, $V_0=6895$ ft/sec and $\sigma=17$ ft. The plotting function is therefore

$$z = \frac{6895}{.43}(e^{.43t} - 1).$$

Conclusions

The main advantage of this procedure, as with all least square methods, is that it eliminates the personal factor involved in visually fitting data to standard functions.

The time element involved in the calculation is not excessive. An experienced computer can usually make the computations on data similar to the example in an hour.

ACKNOWLEDGMENT

Appreciation is expressed to Dr. C. H. Dix of the United Geophysical Company for permission to publish this paper.

FAULTING IN THE BILLINGS OILFIELD, OKLAHOMA, AS INTERPRETED FROM TORSION BALANCE DATA, AND FROM SUBSEQUENT DRILLING*

H. KLAUS†

ABSTRACT

The results of an experimental torsion balance survey of the Billings Oilfield are shown by means of the conventional maps, and of second derivative contour maps. The latter show good and consistent anomalies, which are interpreted as faulting. The survey was made in July, 1937, some time after discovery of Ordovician production in the field, but long before faulting was clearly defined by drilling, and the results were communicated to several oil companies interested in the area or in the method of interpretation. In the meantime, one of the faults limiting the field has been defined in detail by drilling, and the present subsurface interpretation is compared with the original torsion balance predictions with respect to this fault. From the amount of agreement between the two sets of data, it is concluded that the torsion balance can still be used effectively for specialized purposes, particularly the investigation of faulting.

ACKNOWLEDGMENTS

The writer is indebted to Mr. C. C. Toomey, president of Midco Oil Corporation, for geological and historical information concerning the Billings Oilfield; to members of the geologial staff of Tidewater Associated Oil Company, for valuable geological information; and to Mr. J. C. Hughes of Klaus Exploration Co., for preparing the illustrations.

INTRODUCTION

During the past seven years, the torsion balance has been almost completely replaced by the gravity meter in gravimetric reconnaissance work. This development was induced by two principal factors: the greater speed, economy, and accuracy of the gravity meter in measuring gravity differences, and the very incomplete and insufficient exploitation of the greater resolving power of the torsion balance by most operators. Thus, as Heiland[1] points out, "The trend in gravity exploration in the past years indicates the rather remarkable fact that a method of low resolving power (the gravity meter) has replaced one of higher resolving power (the torsion balance)." Heiland proposes to overcome this condition by (1) reduction in the number of quantities measured by the balance, and (2) speeding up of the operation of the balance by various changes in the instrument. While this writer is in full agreement with the second of these suggestions, he wishes to call

* Presented at the annual meeting, Fort Worth, Texas, April 1943.

† Klaus Exploration Company, Lubbock, Texas.

[1] C. A. Heiland, *A rapid method for measuring the profile components of horizontal and vertical gravity gradients.* GEOPHYSICS, Vol. VIII, No. 2, p. 119 (April 1943).

attention to the fact that too much of the utility of the balance would be sacrificed by carrying out the first suggestion to make the method generally serviceable, because it would be applicable only in cases of very simple structure, containing only one density interface of constant strike which could be classed as a "two-dimensional" feature. In practice, however, such features are the exception rather than the rule. The majority of structures of interest in prospecting are complex rather than simple; they will involve several density boundaries more often than one; they will be rather limited in lateral extent more often than not, and the strike of individual density interfaces will change more often than they will stay constant. A further complication will arise from the various regional and "override" contributions, the recognition and elimination of which will be made much more difficult, if not impossible, by adoption of the first suggestion. Therefore, the writer believes that not much could be gained by sacrificing a large part of the higher resolving power of the torsion balance in order to enable it to compete with the gravity meter. In his opinion, the two instruments are not competitors, but have two different fields of application; the gravity meter should by all means continue to be employed as a rapid reconnaissance instrument, while the torsion balance, in its full resolving power, should be applied to the more detailed investigation of gravity meter anomalies, thus reducing the number of anomalies which must eventually be examined by the seismograph.

The fullest possible utilization of the higher resolving power of the torsion balance would be the first prerequisite for gaining and maintaining this appropriate field of application for the instrument, and the present paper is offered in the hope that it may make a contribution in this respect. In a previous paper,[2] the writer has given a short outline of a method to utilize more fully the higher resolving power of the torsion balance. The present paper presents a concrete example of the practical application of this method.

Another purpose of this paper is to call attention to the possibilities for deeper production in many of our old oilfields, since the Billings Oilfield constitutes a representative example. This field staged a remarkable comeback nearly twenty years after it was discovered, and the reserve established by the second cycle of development was more than three times as large as the one found by the initial development (20 million barrels as compared to less than 6.5 million barrels).

[2] H. Klaus, *An introduction to the second derivative contour method of interpreting torsion balance data*, GEOPHYSICS, Vol. III, No. 3, pp. 234 to 246 (July 1938).

HISTORY AND GEOLOGY OF THE BILLINGS FIELD

The field was discovered by surface geology in 1917. The surface rocks consist of sandstones and shales belonging to the Sumner group of early Permian age. The surface structure, and the Pennsylvanian structure down to about 4,000 feet, is a large anticlinal dome, embracing several sections of land within the lowest closing contour. Only a small part of this acreage, representing the very top of the structure,

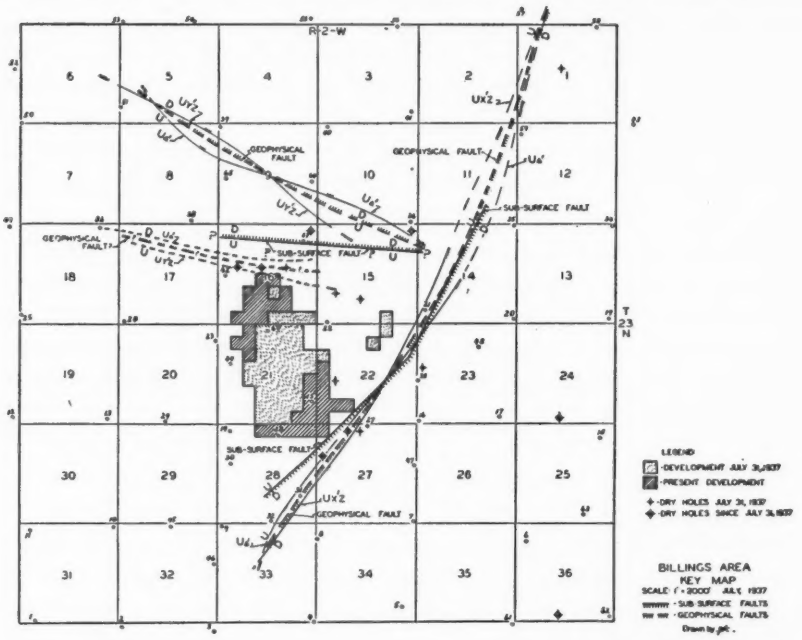

FIG. 1. Key map of the vicinity of the Billings Field, showing the faults limiting the pre-Pennsylvanian tilted wedge, the area of Ordovician production at the time of the survey (stippled), and the area developed since (hachured.) Subsurface interpretation of faulting is shown as solid side-hachured lines, geophysical interpretation of faulting as broken side-hachured lines.

was found productive from Pennsylvanian sands. Most of this production occurred in sections 15 and 22, T 23 N, R 2 W, mainly to the east and north of the deep production.

The pre-Pennsylvanian structure, as it is interpreted from present subsurface data, is a large up-faulted wedge, tilted southwestward between two converging or intersecting faults, and deeply eroded at the top. The pre-Pennsylvanian formations have been stripped off the top of the wedge down to the very base of the Simpson formation.

Down dip, successively younger beds are preserved from erosion, until finally the full Simpson section is present, including the prolific Wilcox sands. Production occurs principally in a north-south striking belt, defined on the west by the oil-water contact, and on the east by the erosional absence of the producing section. The great hazards involved in locating this productive belt merely by exploratory drilling are easily appreciated, and it is not surprising that twelve deep dry holes were drilled in the process. Many of these holes were drilled because the presence of faulting was not known when this exploration started, and it is probable that the full utilization of the geophysical methods then known would have prevented the drilling of several of these holes. It took 13 years, from the time the first deep well was drilled, until commercial production was found in the Ordovician.

The heavy solid lines in Fig. 1 show the subsurface faults bounding the pre-Pennsylvanian tilted wedge, as they are interpreted today from drilling data. The fault on the southeast flank of the structure is defined in detail, while the one on the north flank, in sections 15 and 16, is not definitely established, and might be changed in strike and location by additional subsurface control. The heavy broken lines, hachured on the down-thrown sides, show these faults as interpreted from the torsion balance data.

THE TORSION BALANCE SURVEY

This survey was carried out by Klaus Exploration Company as a research project, during the month of July, 1937. The principal purpose was to see if faulting could be successfully investigated by the second derivative contour method. Faulting was known to exist on the east side of the field at that time, but the strike and extent of the fault were entirely unknown. The geophysical interpretation of this fault, as shown in Fig. 1 in sections 1, 2, 11, 14, 22, 23, 27, 28, and 33, T 23 N, R 2 W, was submitted to several oil companies interested in the field or in the method of interpretation before most of the wells which helped to define this fault were drilled.

The torsion balance survey was laid out as a primary grid or network of stations covering all of T 23 N, R 2 W, with an average distance of one mile between the stations. As this work progressed and began showing anomalies, half-mile stations were added from time to time at critical locations within the primary grid. The observed gradients and curvatures, plotted in the conventional manner, are shown in Fig. 2.

At the time of the survey, the interpretation of torsion balance

data was generally restricted to second derivative profiles, and gravity work. For this reason, the conventional total gravity map is shown herewith. Total gravity was computed from the gradients by simple line integration, adjusted for errors of closure, and contoured at an interval of 0.2 milligals. Station No. 62, in the southeast corner of the area, was used as the base, with an arbitrary value of zero. Besides the values computed for each point, the directional and spacing control

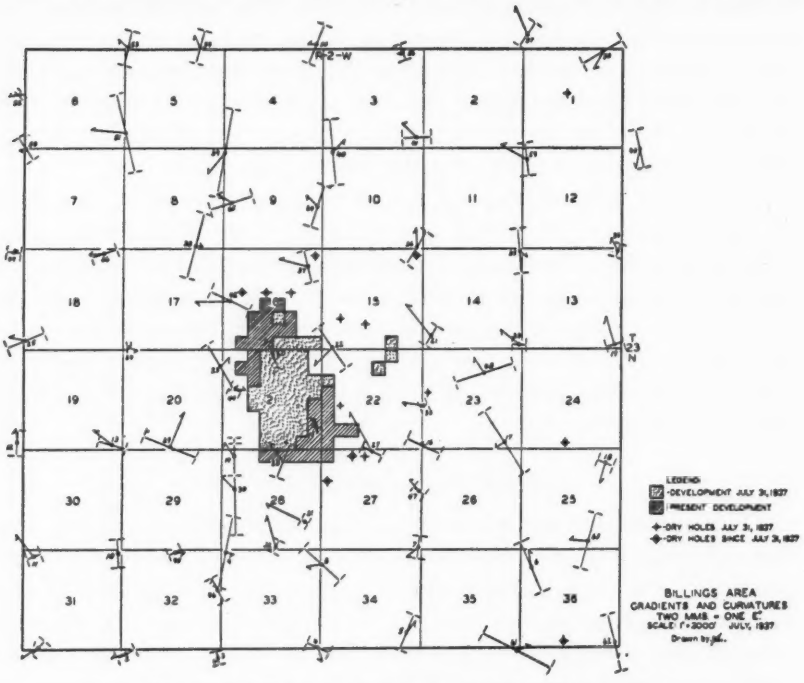

FIG. 2. Gradients and curvatures in the Billings area.

provided by the gradients was used in the contouring, as may easily be seen from an inspection of Fig. 3. Therefore, a gravity meter map with the same control points would hardly be the equivalent of this map. Without the directional and spacing control provided by the gradients, the values given at the control points could be contoured quite differently and much more simply. Much additional gravity meter control would be needed to bring out the details indicated by the gradients.

From an inspection of Fig. 3, it is easily seen that gravity rises regionally to the northwest across the Billings area at a rate of approximately 0.3 milligals per mile, and that the removal of this regional

effect would show a local high in the central part of the township (as well as in several other localities). Faulting on the southeast side of the central high might also be suspected from the configuration of the gravity contours, but could not be proven by the gravity analysis. There are no indications of faulting on the northern flank of the central high, in the gravity picture.

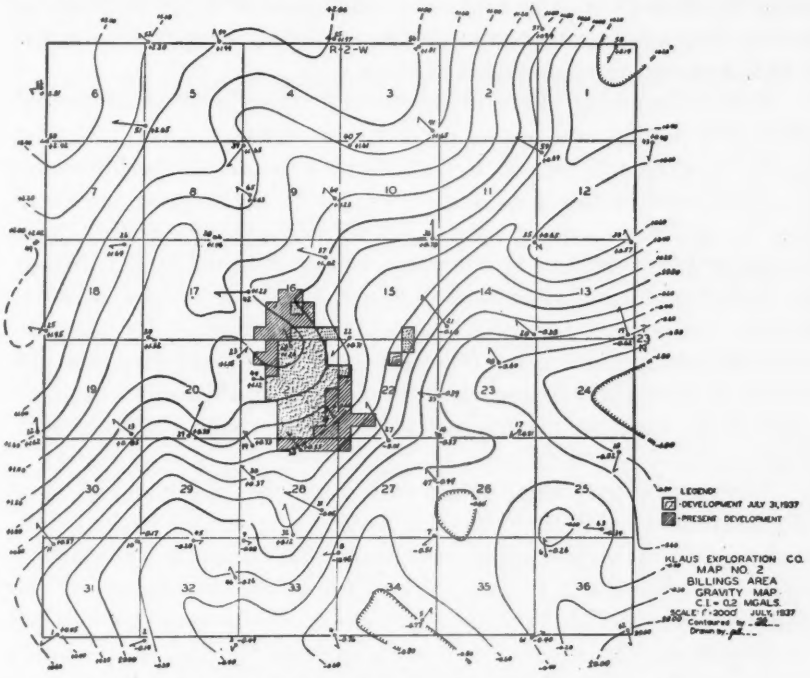

FIG. 3. Total gravity in Billings area. Details of contouring controlled by gradients. Contour interval 0.2 mgl.

SECOND DERIVATIVE ANALYSIS

Instead of utilizing gravity for the structural analysis, the second derivative contour method employs directly the quantities measured by the balance, by contouring them and analyzing the resulting contour patterns. The first step in this work is to rotate the conventional axes of reference, which are N-S and E-W, until one of them coincides with the principal direction of elongation of the torsion balance features. This is done by contouring either the gradients, or the curvatures, and by measuring the principal directions of elongation of the resulting contour configurations, or by measuring the dominant directions of the isogals. In this case, these directions were found to be very

nearly N 30° E and N 60° W. The x'-axis was made parallel to the latter direction, and the y'-axis was made parallel to the former. Thus the new system of axes was rotated through 60 degrees in a counterclockwise direction with respect to the conventional system. Therefore, the angle ϵ, denoting the angle of clockwise rotation in the equations for the new second derivative components in the paper previously mentioned,[3] must be taken as -60 degrees or $+300$ degrees. All second derivative components were recalculated, using this value for ϵ, and then contoured on separate maps.

Before discussing these maps, the relationship between second derivative profiles and second derivative contours will be illustrated briefly by graphical means. Fig. 4a shows a theoretical profile of the U_{xz} component across a subsurface step, with the stepped-up side in the $+x$ direction, and the strike parallel to the y-axis. Such a step, involving a vertical density boundary, could be caused by faulting, or by rapid lateral gradation from lighter material to heavier material in the $+x$ direction. The latter case is often encountered, for instance, in the Permian Basin area of West Texas and New Mexico, and the former is universally found in areas of structural deformation. The peak of the gradient maximum occurs exactly above a vertical subsurface step.

The contour equivalent of this profile is shown in Fig. 4b. The line of the profile coincides with the x-axis. The heavy broken line, hachured on the stepped-down side, shows the trace of the subsurface step. This trace is seen to coincide with the axis of the maximum. The definite elongation of the contour pattern should be noted, as it is one of the principal characteristics of such patterns. In Fig. 4b, the information of Fig. 4a has been extended into the horizontal plane, or, if you will, a third dimension has been added, since the contours are the equivalent of an infinite number of profiles similar to and parallel to that of Fig. 4a, but slowly changing in the $+y$ and $-y$ directions.

Similarly, Fig. 5a shows a theoretical profile of the U_Δ component of the curvatures across the same subsurface step. In Fig. 5a, the positive direction is defined as parallel to the y-axis, or vertical to the plane of the paper, while the negative direction is parallel to the x-axis, in the plane of the paper. The main point to note, for general application, is that the curvatures on the up-side of the step are parallel to its strike, while those on the down-side are at right angles to the strike. The steep slope of the central part of the curve is also a diagnostic feature of the U_Δ anomaly.

[3] H. Klaus, *op. cit.*, p. 238.

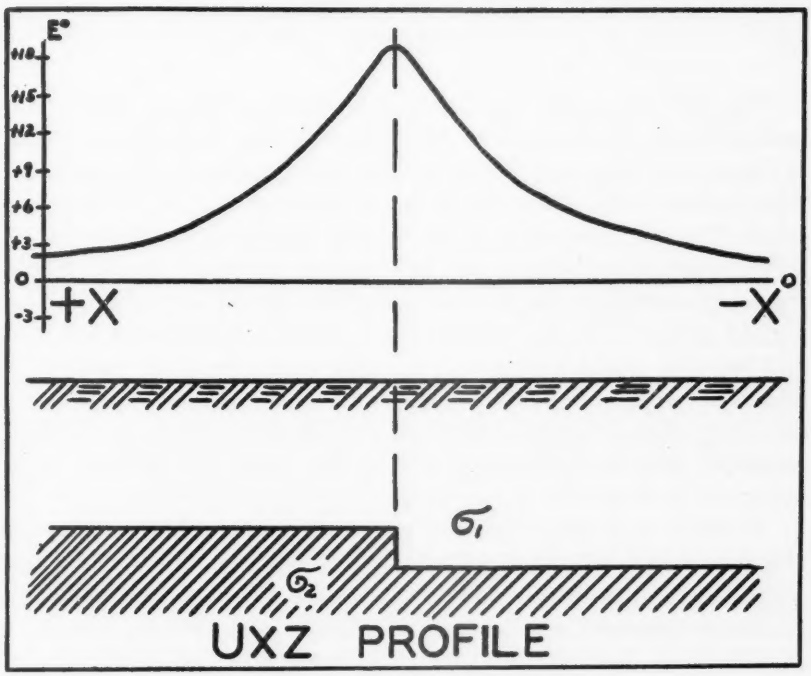

FIG. 4-a. U_{zz} profile across subsurface step.

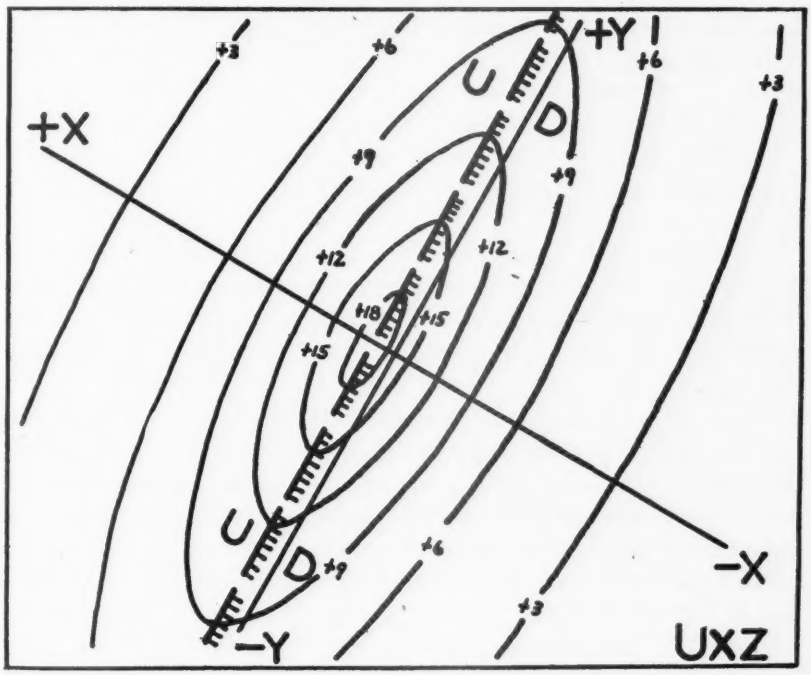

FIG. 4-b. U_{zz} contours for the step shown in Fig. 4-a.

Fig. 5b is the contour equivalent of the profile of Fig. 5a. The heavy broken line shows the trace of the subsurface step. Note the crowding of the contour lines near this trace; this is the diagnostic feature mentioned above which corresponds to the steep central slope of the U_Δ profile. The positive values on the up-side represent curvatures parallel to the strike of the step, and the negative values on the down-side represent curvatures normal to the strike of the step. For a step parallel to the x-axis, the entire pattern would be rotated through 90° and the signs would be reversed, since the negative values would then represent curvatures parallel to the strike; hence, they would occur on the up-side of the step. Similarly, the positive values would then represent curvatures at right angles to the strike; hence, they would occur on the down-side of the step.

In the second derivative contour maps of the Billings area, only the evidence for faulting is marked by line symbols, and the evidence for folding and truncation is neglected, since the paper is specifically limited to a discussion of faulting. For this reason, the $2U_{x'y'}$ contour map has been omitted, since the $2U_{x'y'}$ component has no bearing on the faults.

Fig. 6 shows the $U_{x'z}$ component of the gradient in the Billings area, contoured at an interval of 5 Eoetvoes units. The axis diagram in the right margin of the figure, above the title, shows the orientation of the new system of axes, and the direction of the gradient components which is indicated by positive or negative values of $U_{x'z}$.

The boxed-in value near the center of the map is the average of all $U_{x'z}$ values in the township, and represents a first approximation to the regional.

Note the definite elongation of the maximum east of the center of the township. This maximum is interpreted as due to a fault, because of its pronounced elongation, and because of its excess of positive values over the amount required by simple folding of the Billings structure.

The case is not nearly as pronounced for the fault patterns in the contours of the $U_{y'z}$ component, but we have the definite elongation for the northern fault, in sections 5, 6, 8, 9, and 15, and the elongation, as well as some excess of the negative closure over the requirements of a symmetrical anticlinal pattern, for the southern fault, in sections 15, 16, and 17. The latter is shown by a broken line simply for the reason that it was not considered pronounced enough to be taken into consideration, in the original interpretation of the data made in July, 1937. Both patterns are minima, because the up-sides of the respective steps are to the SSW, while the positive branch of the y'-axis is di-

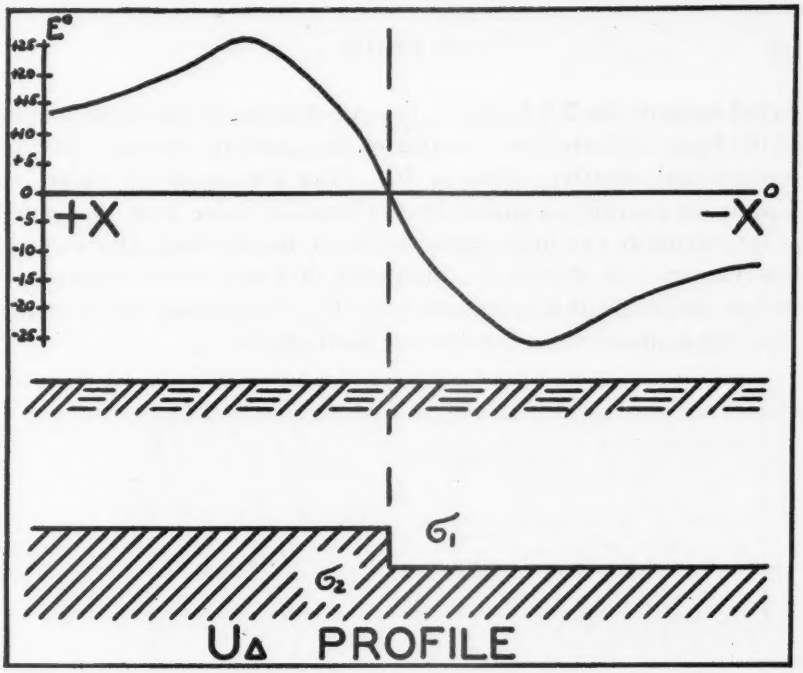

FIG. 5-a. U_Δ profile across subsurface step.

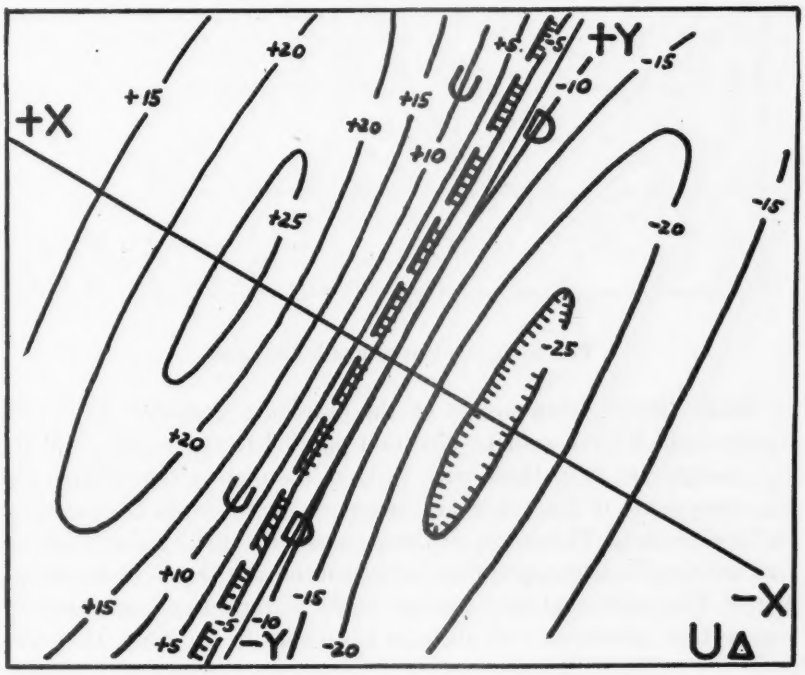

FIG. 5-b. U_Δ contours for the step shown in Fig. 5-a.

rected towards the NNE. Again, the axis-diagram in the right margin of the figure indicates the direction of the gradients corresponding to positive and negative values of $U_{y'z}$. The average of all values of $U_{y'z}$ in the township is shown by the boxed-in value near the center of the township, as a first approximation to the regional. This value is less than one-half of an E. U., indicating that most of the regional effect on the gradients is contained in the $U_{x'z}$ component, and that the $U_{y'z}$ map contains almost exclusively local effects.

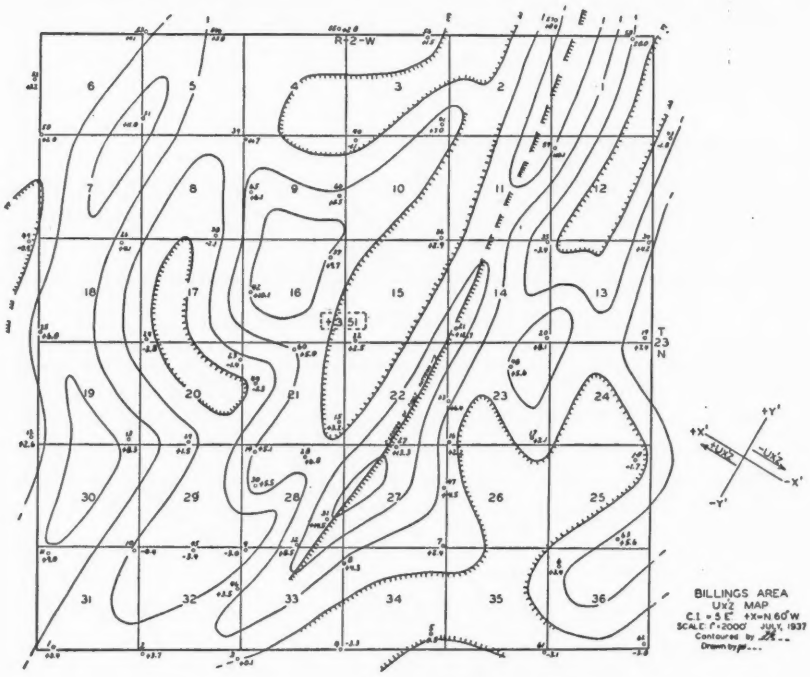

FIG. 6. $U_{x'z}$ contour map of Billings area.

While the $U_{x'z}$ component of the gradients portrays only those features which have a strike direction parallel to the y'-axis, and the $U_{y'z}$ component only those with a strike parallel to the x'-axis, the $U_{\Delta'}$ component of the curvatures is equally sensitive to both of these strike directions. Therefore, all three steps indicated by the gradients find their equivalent expressions in the contours of the $U_{\Delta'}$ component, Fig. 8. The individual patterns are badly distorted and cut down by the mutual interference of all local anomalies in the area. However,

the sharp central reversals of these patterns are much less affected by this interference than the outer portions of the component positive and negative closures, and this is another reason why these reversals are, in practical work, the most diagnostic features of curvature patterns over subsurface steps. In the case of the fault on the SE flank of the structure, the strike of which is very nearly parallel to the y'-axis, this reversal proceeds from negative values on the down-side of the step to positive values on the up-side. This reversal is enhanced by the

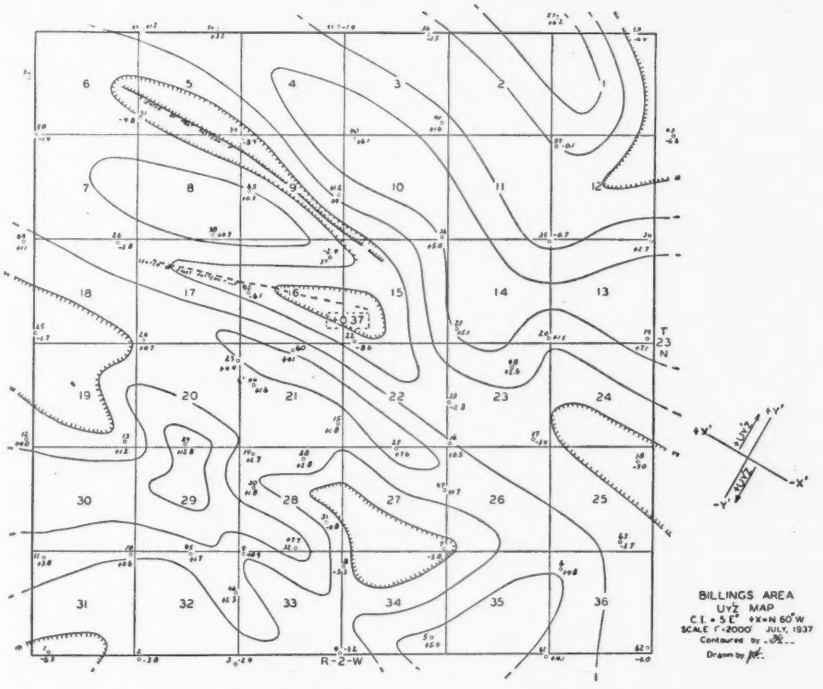

FIG. 7. $U_{y'z}$ contour map of Billings area.

presence of an anticlinal pattern, the axis of which is located on the up-side of the step. This pattern will not be discussed in detail, and is mentioned merely for the purpose of pointing out the difficulty of separating the fault pattern from the anticlinal pattern quantitatively. The sharp central reversal of this pattern is generally well preserved with exception of the neighborhood of section 11, where it is badly distorted by a WNW-ESE striking synclinal pattern. In the area from section 14 to section 33, however, the reversal is suitable

for the qualitative interpretation of the location and strike of the fault.

The two northwestern faults are very nearly parallel to the x'-axis. Therefore, they involve sharp reversals from positive values, on the down-sides, to negative values, on the up-sides of the respective subsurface steps. The northern step involves a reversal of sufficient lateral extent to make it suitable for qualitative interpretation. A

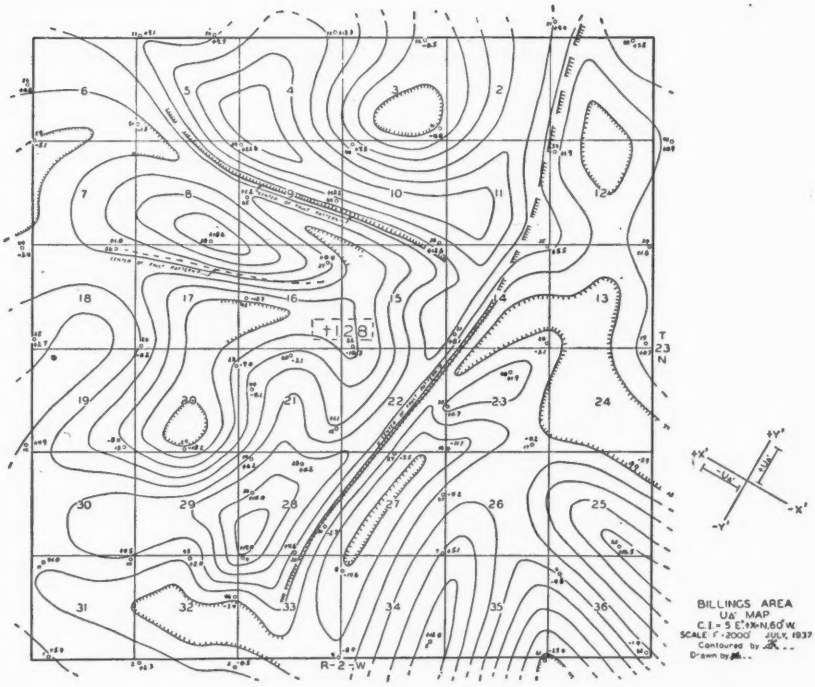

FIG. 8. $U_{\Delta'}$ contour map of Billings area.

quantitative analysis, however, is made difficult, if not impossible, by the presence of a well defined synclinal pattern on the down-side of the step.

The reversal of the southern step, principally in sections 16 and 17, does not have sufficient lateral extent to be interpreted without hesitation as a step anomaly. Therefore, it was not considered in the original interpretation, and it is marked by a broken line and a question-mark in Fig. 8. If a step anomaly actually is involved, its quan-

titative analysis is made very difficult by the presence of an anticlinal pattern on its up-side.

After the contour patterns of each second derivative component have been evaluated separately and marked by line symbols, the latter are assembled on the so-called key map, for final interpretation. Fig. 1 serves as the key map, as far as the faulting is concerned. For each fault, the line symbols marking the center of the $U_{\Delta'}$ reversal and the center of the respective gradient anomaly are shown by light lines, and the center of the corresponding step anomaly by a heavy broken line. This line represents a compromise between the curvature and gradient evidence, and is drawn only when these two types of evidence show sufficiently close agreement. For the southeastern fault, the degree of agreement is considered very satisfactory, for a reconnaissance survey, for that portion of the fault extending from the SW corner of section 14 to the center of section 33. In the neighborhood of section 11, the agreement is poor, possibly due to the distortion of the $U_{\Delta'}$ pattern mentioned above, but this locality is outside of the Billings structure proper, and outside of the geological control.

In the case of the northwestern faults, the agreement between the gradient and curvature evidence may be called "fair."

The heavy broken lines, which represent the geophysical fault interpretations, can now be compared with the heavy solid lines, which are the geological subsurface interpretations of the drilling results. In making the comparison, it should be taken into consideration that most of the wells did not penetrate very deeply into the formations below the pre-Pennsylvanian unconformity, and that, therefore, only the uppermost portions of the fault-planes could be considered in the geological analysis. On the other hand, as will be shown below, there are good reasons for believing that the major part of the fault effects measured by the torsion balance arises from the density contrast between basement and sedimentary rocks, at depth. Therefore, the effects of slight hade and/or curvature of the fault plane may be responsible for the divergence between the geological and geophysical fault lines in sections 27 and 28. In sections 14, 22, and 23, the agreement between the geological and geophysical interpretations is very satisfactory.

The subsurface fault in sections 15 and 16 is admittedly questionable, as there is no close well control at the present time. Faulting is thought to occur somewhere between the wells in the central part of section 16, and the dry hole in the NE corner of the section. Therefore,

a fair comparison between the geological and geophysical evidence for faulting in this locality should be delayed until closer well control is available. In a general way, however, the geological and geophysical data agree on interpreting the pre-Pennsylvanian structure as an up-faulted wedge. If this type of structure had been considered at the outset of the deep drilling campaign, as it easily could have been from a survey such as the one under discussion, a good many dry holes would have been avoided in the search for the deeper production.

SEMI-QUANTITATIVE TEST

As has been pointed out previously,[4] it is not advocated by the writer that the torsion balance be used for quantitative work. The qualitatively correct recognition of the number, location, and type of definite subsurface elements constituting a complex structure is the proper field of application of the balance, and the quantitative work should be left to the reflection seismograph. However, it is useful at times to check the qualitative conclusions reached from an analysis of torsion balance data by a semi-quantitative test. In the present case, so many anomalies of the step, fold, and buried topography type combine to form one complex anomaly that it is exceedingly difficult to separate out one specific element quantitatively. This is especially true of the $U_{\Delta'}$ anomalies, as pointed out above, and no attempt will be made, therefore, to isolate the $U_{\Delta'}$ anomaly of any one of the steps. Since the geological control is insufficient near the northwestern steps, the $U_{y'z}$ anomalies are also ruled out. There remains the gradient evidence for the southeastern step, which is found in the $U_{x'z}$ component, and an attempt shall be made to isolate this anomaly quantitatively. As has been pointed out above, the principal $U_{x'z}$ evidence for this step was the definite elongation of the positive closure involved, and its excess over the requirements of symmetry. In the general nature of structural deformation in this area, local uplift is accomplished by warping and by faulting. Where warping alone is involved, the corresponding gravity anomalies remain symmetrical even in the case of subsequent tilting, because the tilting produces a constant regional effect which does not change the symmetry, when reckoned from the regional level instead of absolute zero. Asymmetry, on the other hand, is indicative of faulting, or of relative displacement of one basement block with respect to another. However, the gravi-

[4] H. Klaus, *op. cit.*, p. 245.

metric asymmetry is a measure only of the *minimum* amount of faulting. The actual amount could be greater, depending on the ratio of dip to faulting in the structural relief of the faulted flank of the uplift. By this reckoning, the minimum $U_{z'z}$ anomaly of the southeastern fault is 3.7 E. U., determined as follows: The complete $U_{z'z}$ anomaly of the Billings structure is a large anticlinal pattern, modified into a truncation pattern by a subsidiary minimum in the vicinity of section 15, and a subsidiary maximum in the vicinity of section 16. As far as the total $U_{z'z}$ anomaly is concerned, these features can be neglected, and the principal or bracketing closures alone need be considered. These are the maximum in sections 14, 22, 27, and 28, and the minimum in sections 8, 17, 20, and 29. The relief of the maximum is 11.0 E. U., measured from the value of station No. 31 (+14.5 E. U., the maximum of the east flank of the structure) to the regional level (+3.5 E. U.), and the relief of the minimum is 7.3 E. U., measured from station No. 24 (−3.8 E. U., the minimum on the west flank of the structure), to the regional level. The excess of the maximum over the minimum amounts to 3.7 E. U., and this is the minimum contribution of the southeastern fault to the positive closures in sections 14, 22, 27, and 28.

The gravimetric effect of the fault is a summation of the effects of individual juxtapositions of masses with different densities. In the shallower portions of the fault, immediately below the pre-Pennsylvanian unconformity surface, we have Mississippian on the down-thrown side in juxtaposition with Ordovician limestones, dolomites, and small amounts of sandstones and shales. It is thought that very little, if any, density contrast exists between these formations, judging from their lithological characteristics, although the writer has no exact density measurements at his disposal to support this judgment. At depth, there must be at least 900 feet of juxtaposition of Cambro-Ordovician sediments, on the down-thrown side, with pre-Cambrian basement rocks, on the up-thrown side, according to estimates based on subsurface data. This juxtaposition should extend from a depth of about 5000 feet to a depth of about 5900 feet. This geologic estimate of the throw at depth is also a *minimum*. It could be larger, since several periods of rejuvenation and truncation of the fault are indicated. It will be shown below that this fault at depth will reproduce the minimum $U_{z'z}$ anomaly at a density contrast of 0.17 between Cambro-Ordovician sediments and pre-Cambrian igneous and metamorphic basement rocks.

The general equation of U_{zz} for a vertical fault is given by:

$$U_{zz}=2\gamma\sigma \log (r_2/r_1)$$

where γ is the gravitational constant, or $66.64 \cdot 10^{-9}$ C.G.S., σ the effective density difference, and r_1 and r_2 the distances from the surface to the upper and lower edges, respectively of the density step, measured in the x, z plane. While this equation is rigidly valid only for steps of infinite strike, it is correct within less than one per cent in the present case, since the dimension along the strike is very large when compared to the depth and the throw. Substituting the values given above into this equation for a point x_0' vertically above the trace of the fault, or along the axis of the $U_{z'z}$ maximum, we have $U_{z'z}=2\times66.64 \times10^{-9}\times0.17\times\log (5900/5000)=3.76$ E. U. Therefore, the order of magnitude of the fault as postulated from the geological data agrees well with the minimum value of the $U_{z'z}$ anomaly as derived from the torsion balance data.

CONCLUSION

The present concept of the pre-Pennsylvanian structure at Billings, as an upfaulted wedge between two converging or intersecting faults, was clearly expressed by the torsion balance data before this concept was developed from drilling results. The fault limiting the wedge on the southeastern side has now been defined in detail by drilling, and its present geological interpretation agrees closely with the qualitative geophysical interpretation made in 1937. It is concluded, therefore, that the torsion balance, when used in its full resolving power, or in the second derivative phase of interpretation, still has considerable value as an exploration tool, particularly for the investigation of step anomalies, or faults and rapid changes of facies. It is suggested that the proper field of application of the balance is the closer examination of gravity anomalies found by the gravity meter, to determine which of these anomalies is worth a detailed seismograph survey.

USE OF THE GRAVITY METER IN ESTABLISHMENT OF GRAVITY BENCH MARKS*

E. V. McCOLLUM† AND ANDREW BROWN‡

ABSTRACT

Data are presented showing comparisons between gravity meters and networks of gravity meter bench marks. Methods of adjustment of networks for closure are suggested. Ties to pendulum stations of the U. S. Coast and Geodetic Survey and the Dominion Observatory of Canada afford a basis for the calibration of the gravity meters used and the evaluation of the gravity meter bench marks in terms of the world gravity network. Probable errors and accuracies are discussed.

Relative gravity measurements in gravity surveying are similar to the determination of elevations in civil engineering; therefore, a system of gravity bench marks, similar to the precise elevation bench marks of the U. S. Coast and Geodetic Survey, would prove to be very valuable in gravity surveys. Much redrafting of maps and recalculation of gravity data has been necessary since the entrance of the gravity meter into geophysical prospecting because of the lack of a common gravity datum upon which to base gravity surveys. A system of precise gravity bench marks would also make possible the uniform calibration of gravity meters.

Whereas, the U. S. Coast and Geodetic Survey, the Dominion Observatory of Canada, and other similar governmental agencies, have established a considerable number of pendulum stations in their respective countries, such stations cannot be used directly as gravity bench marks in prospecting with the gravity meter due to, (a) lack of precision, and, (b) insufficient areal distribution. However, the pendulum stations serve a very useful purpose in calibrating gravity meters and tying to the world gravity network.

Since gravity meters have the requisite gravity sensitivity, it follows that they can be used for the establishment of gravity bench marks. During the last three years, the Mott-Smith Corporation and the Canadian Geophysical Company, Ltd., have established approximately 800 gravity bench marks in 13 states of the United States and two provinces of Canada. The locations of the gravity bench marks

* Presented at the annual meeting, Fort Worth, Texas, April 1943.

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‡ Mott-Smith Corporation, Houston, Texas.

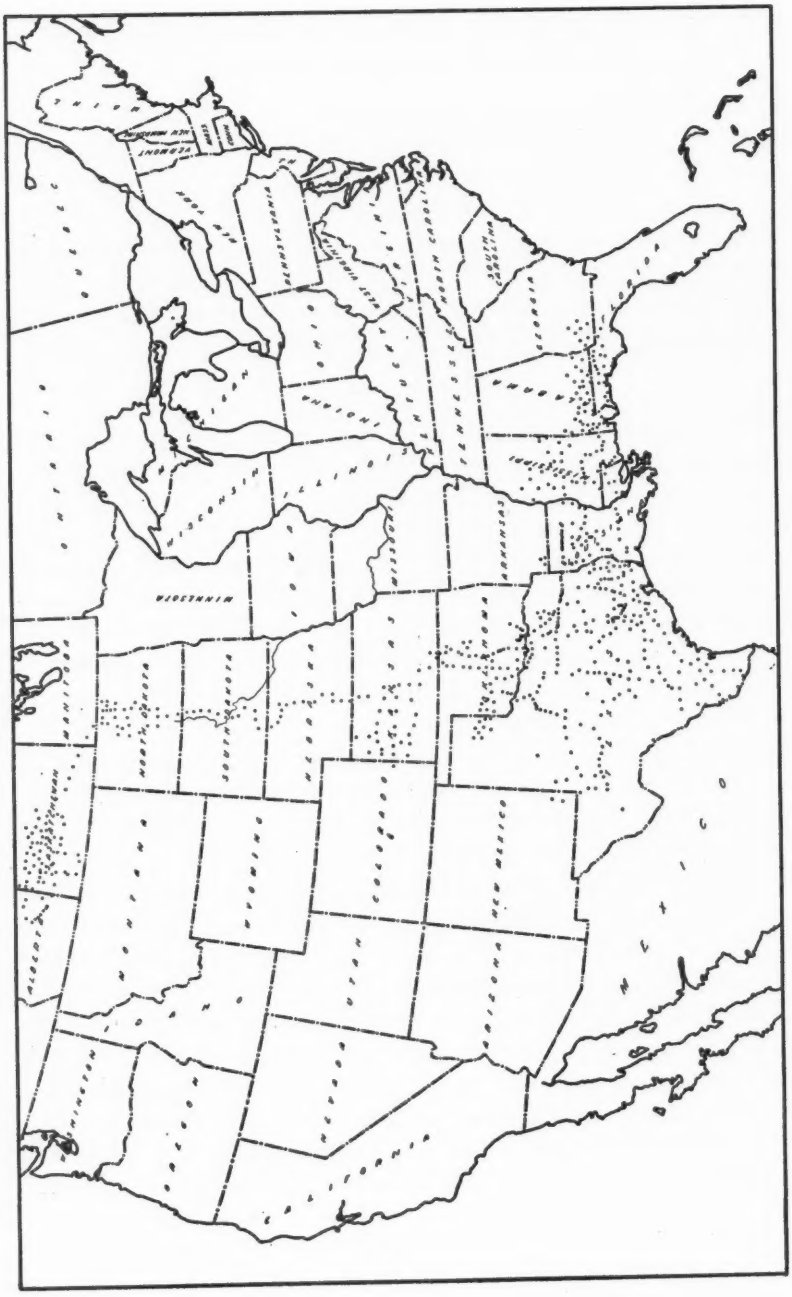

FIG. 1. Distribution of gravity meter bench marks in the United States and Canada.

are shown in Fig. 1. 109 pendulum stations were occupied and approximately 100,000 miles were driven in laying out the gravity bench marks. Null type gravity meters, linear in scale, and with gravity sensitivity substantially 0.1 milligal per scale division, were used in this work. The method of "looping"[1] was employed in setting the stations.

It will be readily understood that if a plurality of gravity meters with linear scale constant were used to run a network of gravity stations, and that if the several gravity meters used duplicated at least a portion of the work of some other meter or meters; and, furthermore, if it were required that several of the stations be coincident with pendulum stations, it would be possible to formulate a least square solution that would furnish the constants of all the instruments and the gravity values of all the stations, provided only that the number of observational quantities exceeded the number of unknown quantities. Such a general solution is quite tedious, and, furthermore, all data must be available at the time the solution is made. Considerable clarity and utility may be gained by resolving the general problem into the following partial solutions:

1. Matching of gravity meters.
2. Adjustment of gravity meter networks.
3. Adjustment to pendulum stations.

MATCHING OF GRAVITY METERS

About 50 gravity meters have been compared at a series of five matching (calibration) stations near Houston, Texas, for which the overall gravity difference is approximately 70 milligals. The matching data makes possible the conversion of the readings of all instruments to a selected instrument.

If the scale reading of an arbitrary instrument is designated by R_i and the reading of the selected instrument S_i, the readings on the two instruments can be related in functional form by

$$\alpha + \beta R_i = S_i \qquad (1)$$

where α and β are constants.

As a numerical example, the observational equations linking one typical arbitrary instrument with the selected instrument at five comparison stations are,

[1] L. L. Nettleton, *Geophysical Prospecting for Oil*, p. 38, McGraw-Hill (1940).

$$\begin{aligned} \alpha + \quad 0.0\beta &= \quad 0.0 \\ \alpha + 114.1\beta &= 143.51 \\ \alpha + 292.1\beta &= 367.57 \\ \alpha + 602.9\beta &= 758.15 \\ \alpha + 654.1\beta &= 822.37 \end{aligned} \tag{2}$$

A least squares solution* of (2) gives $\beta = 1.25730$. The probable error in β is $\epsilon_\beta = 0.28 \times 10^{-8}$. A study of data accumulated at the matching stations reveals that the several meters are mutually matched to a precision of 3 parts in 10,000. The least squares solution of equations similar to (2) will be more fully discussed in a later section entitled "Adjustment to Pendulum Stations."

Mr. Craig Ferris[2] has pointed out that gravity meters may also be matched if data are available for a plurality of pairs of stations wherein the several pairs are not necessarily tied together. If the gravity difference obtained at a pair of stations on one instrument be called p_i and the gravity difference measured by the standard instrument be q_i, the equation connecting them may be written as,

$$p_i = \beta q_i. \tag{3}$$

If measurements are taken at n pairs of stations, the matching constant, β, and its error, ϵ_β, are[3]

$$\beta = \sum p_i q_i / \sum q_i^2 \tag{4}$$

$$\epsilon_\beta = \pm .6745 [\sum (\beta q_i - p_i)^2 / (n - 1) \sum q_i^2]^{1/2} \tag{5}$$

where the summation signs include all integral values $1, 2, 3, \cdots, n$.

ADJUSTMENT OF GRAVITY METER NETWORKS

In establishing the gravity bench marks, measurements were taken around closed loops insofar as possible. The loops were then adjusted by methods based on least square solutions.

* R. Meldrum Stewart, Dominion Astronomer, Ottawa, has kindly pointed out in a personal communication that the solutions given to the sets of equations 1, 3 and 9 are first approximations, which are strictly correct only if the observed quantities R_i, q_i, and S_1, S_2, $\cdots$, respectively are free from error, observational error being restricted to S_i, p_i, and g_1, g_2, $\cdots$, in the respective cases. This topic is discussed in *Phil. Mag.*, Vol. 40, pp. 217–27 (1920). However, it is not likely that the results of the rigorous solution would differ materially from those given.

[2] Private communication.

[3] Davis and Brenke, *The Calculus*, Tables p. 6, Macmillan (1922).

In the case where only one closed loop exists, let $q_1, q_2, q_3 \cdots q_n$ be the most probable gravity values, and let $S_1, S_2, S_3 \cdots S_n$ be the observed gravity values around a loop of n sides. If the observations are of equal weight, the observation equations are,

$$\begin{aligned} q_1 &= S_1 \\ q_2 &= S_2 \\ q_3 &= S_3 \\ &\cdots\cdots \\ &\cdots\cdots \\ q_n &= S_n \end{aligned} \tag{6}$$

To the observation equations must be added the equation of condition,

$$q_1 + q_2 + q_3 + \cdots + q_n = 0. \tag{7}$$

The least squares solution of Eqs. 6 and 7 for the i^{th} side gives,

$$q_i = S_i - (1/n)\sum S. \tag{8}$$

It is to be noted from Equation 8 that the misclosure, $\sum S$, should be equally distributed among the various sides of the closed loop.

In the event that a network of closed loops exist, the adjustment is

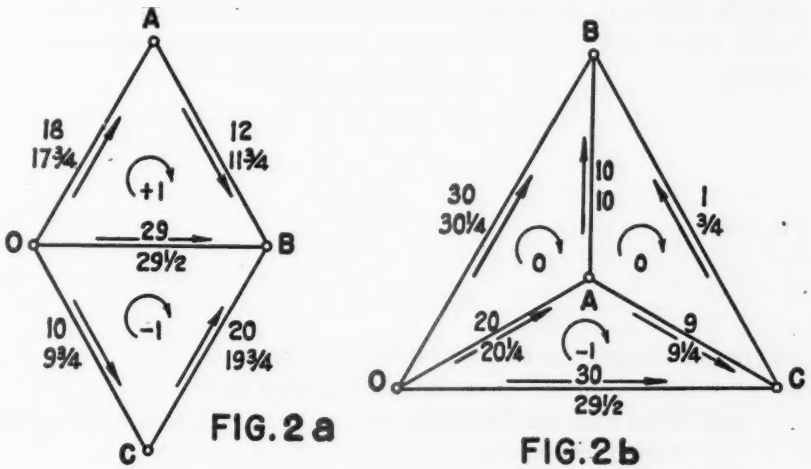

FIG. 2. Schematic networks of gravity meter bench marks illustrating adjustment by least squares.

somewhat more complicated. The general procedure used is illustrated numerically in Fig. 2. In each of the diagrams the misclosure on each of the loops, taken in a clockwise direction, is indicated by a number in the center of the loop. On each of the sides the upper figure, such as 18, along *OA* of Fig. 2a, denotes the observed gravity, and the lower figure, such as $17\frac{3}{4}$, gives the value obtained by a least squares adjustment. Studies of Figs. 2a and 2b, together with similar networks, have revealed that,

1. Loops with small misclosures need little adjustment, and,
2. Sides common to loops with misclosures opposite in sign require relative strong adjustments.

Whereas, the actual adjustment of the loops was done by inspection based on the rules formulated above, very little difficulty was encountered, since a fair balance of positive and negative closure of adjoining loops exists throughout the network. It is believed that a rigorous least squares solution would give values for the individual stations that would agree within a few hundredths of a milligal from those adopted.

ADJUSTMENT TO PENDULUM STATIONS

As previously mentioned, 109 pendulum stations observed by the U. S. Coast and Geodetic Survey and the Dominion Observatory of Canada were occupied during the process of establishing the gravity meter bench marks. The following observation equations may be written,

$$\begin{aligned} g_0 + kS_1 &= g_1 \\ g_0 + kS_2 &= g_2 \\ &\cdots\cdots \\ &\cdots\cdots \\ g_0 + kS_n &= g_n \end{aligned} \tag{9}$$

where g_0 is the gravity at an arbitrary starting point
k is the constant of the selected gravity meter
S_i is the scale reading of the gravity meter referred to the arbitrary starting point
g_i is the gravity measured by the pendulum.

A least squares solution of (9) gives the normal equations,

$$\begin{aligned} ng_0 + k \cdot \sum S_i &= \sum g_i \\ S_i g_0 + k \cdot \sum S_i^2 &= \sum S_i g_i. \end{aligned} \tag{10}$$

Solving (10) for k and g_0 gives,

$$k = [n \sum S_i g_i - \sum S_i \sum g_i] / [n \sum S_i^2 - (\sum S_i)^2] \tag{11}$$

$$g_0 = [\sum S_i^2 \sum g_i - \sum S_i \sum S_i g_i] / [n \sum S_i^2 - (\sum S_i)^2]. \tag{12}$$

The gravity misclosure of closed loops may be used to estimate the error, e, in the gravity differences between pairs of stations. Let $q_1, q_2, q_3, \cdots, q_n$, be the gravity differences obtained along a line of gravity stations. The total gravity change, Q, is,

$$Q = q_1 + q_2 + q_3 + \cdots + q_n. \tag{13}$$

If all of the q's have been measured with equal precision, the cumulative error, E, may be shown to be[4]

$$E = \sqrt{n} \cdot e \tag{14}$$

where e is the error in each gravity difference between successive pairs of stations.

In the particular case where the line of gravity stations forms a closed loop of n sides, the cumulative error is given by the misclosure $\sum S$ so that

$$e = (\sum S) / \sqrt{n}. \tag{15}$$

In Table I, closure data and errors for 12 typical loops are presented. The average value of 0.0185 milligals was obtained for e.

TABLE I

CLOSURE DATA AND ERRORS FOR 12 TYPICAL LOOPS

Loop no.	*Distance around loop in miles*	n	$\sqrt{n}$	$\sum S$	e
A	455	18	4.2	$-.04 \times 10^{-3}$	$.010 \times 10^{-3}$
B	697	32	5.6	+.04	.007
C	403	16	4.0	−.10	.025
D	504	25	5.0	−.33	.066
E	444	22	4.7	+.03	.006
F	563	21	4.6	+.11	.024
G	370	16	4.0	+.03	.008
H	359	15	3.9	+.11	.029
I	527	26	5.1	+.08	.016
J	387	25	5.0	−.05	.010
K	260	14	3.7	−.04	.011
L	604	24	4.9	+.05	.010
				Average	.0185

[4] Leroy D. Weld, *Theory of Errors and Least Squares*, p. 166, Macmillan (1922).

The probable errors of k and g_0 can be determined by a method outlined by Weld.[5]

The standard error can be obtained from the formula,

$$\epsilon_s = \pm 0.6745[\sum p_i^2/(n-l)]^{1/2} \tag{16}$$

where $p_i = (g_0 + kS_i) - g_i$

n = number of observations

l = number of unknowns

then ϵ_k, and ϵ_0, the standard error in g_0, are,

$$\epsilon_k = \epsilon_s\{n/[n\sum S_i^2 - (\sum S_i)^2]\}^{1/2} \tag{17}$$

$$\epsilon_0 = \epsilon_s\{[\sum S_i^2]/[n\sum S_i^2 - (\sum S_i)^2]\}^{1/2}. \tag{18}$$

In Table II are tabulated the most probable gravity values, $(g_0 + kS_i)$, the pendulum values, g_i, and the residuals, ρ_i, for the American and Canadian pendulum stations[6] occupied by the gravity meters. Stations marked with an asterisk were not used in the least squares solution because of their large residuals. The average residual, without regard to sign, for the 100 pendulum stations used in the solution, is 1.33 milligals.

TABLE II

RESULTS OF ADJUSTMENT TO 109 PENDULUM STATIONS IN THE U. S. AND CANADA. ρ_i ARE THE RESIDUALS BETWEEN THE GRAVITY METER AND PENDULUM OBSERVATIONS

Station	g_0+kS_i	g_i	ρ_i	*Station Location*
6*	979.53587	979.548	$+12.13\times10^{-3}$	Rayville, Louisiana
9	979.08177	979.084	+ 2.23	Laredo, Texas
10	979.29005	979.292	+ 1.95	Austin, Texas
41	979.75614	979.760	+ 3.86	Wallace, Kansas
73	979.57203	979.571	− 1.03	Denison, Texas
76	980.62490	980.628	+ 3.10	Bismarck, North Dakota
93	979.35080	979.350	− 0.80	Wilmer, Alabama
94*	979.55039	979.557	+ 6.61	Aliceville, Alabama
97	979.42551	979.427	+ 1.49	Nacogdoches, Texas
118*	980.42509	980.432	+ 6.91	Pierre, South Dakota
144	979.43051	979.433	+ 2.49	Alexandria, Louisiana
145	979.46949	979.471	+ 1.51	Laurel, Mississippi
167*	979.61125	979.605	− 6.25	Arkansas City, Arkansas
189*	980.81225	980.819	+ 6.75	Towner, North Dakota
206*	980.21062	980.216	+ 5.38	Valentine, Nebraska
285	979.29489	979.296	+ 1.11	Sabine, Texas
300	979.66417	979.666	+ 1.83	Wapanucka, Oklahoma
301	979.66291	979.662	− 0.91	Troy, Oklahoma

* Stations not used in least squares solution due to large residuals.

[5] *Op. cit.*, p. 183.

[6] Obtained from *Principal Facts for Gravity Stations*, Parts 1 to 6 inclusive, U. S. Coast and Geodetic Survey, and *Gravity and Isostasy in Canada*, Publications of the Dominion Observatory, Vol. XI, No. 3 (1936).

TABLE II—*Continued*

Station	g_0+kS_i	g_i	ρ_i	*Station Location*
306	979.51802	979.518	− 0.02	Saline #1, Texas
307	979.51910	979.520	+ 0.90	Saline #2, Texas
311	979.26762	979.267	− 0.62	Damon #1, Texas
312	979.25568	979.257	+ 1.32	Damon #2, Texas
399	979.36616	979.368	+ 1.84	Marianna, Florida
400	979.35409	979.353	− 1.09	Baton Rouge, Louisiana
402	979.29384	979.294	+ 0.16	Pierce Junction, Texas
403	979.28530	979.287	+ 1.70	Blue Ridge, Texas
404	979.28297	979.283	+ 0.03	Sugarland, Texas
406	979.32524	979.326	+ 0.76	Beaumont, Texas
407	979.33615	979.337	+ 0.85	Cleveland, Texas
420*	979.88436	979.877	− 7.36	Hays, Kansas
454	980.19897	980.195	− 3.97	Crabb, Nebraska
456*	979.70777	979.698	− 9.77	Bullard, Kansas
714*	979.32528	979.330	+ 4.72	Welsh, Louisiana
715	979.30950	979.310	+ 0.50	Grand Chenier, Louisiana
716	979.38049	979.383	+ 2.51	Oakdale, Louisiana
717	979.41170	979.414	+ 2.30	Sandel, Louisiana
718	979.50665	979.510	+ 3.35	Kingston, Louisiana
719	979.51990	979.524	+ 4.10	Vernon, Texas
720	979.22298	979.223	+ 0.02	Midland, Texas
721	979.30153	979.302	+ 0.47	Sweetwater, Texas
725	979.08173	979.080	− 1.73	Port Isabel, Texas
726	979.11124	979.111	− 0.24	Alice, Texas
727	979.14858	979.145	− 3.58	Corpus Christi, Texas
728	979.25144	979.251	− 0.44	Bay City, Texas
730	979.27856	979.279	+ 0.44×10^{-3}	Rosenberg, Texas
731	979.28422	979.283	− 1.22	Wallis, Texas
733	979.30082	979.303	+ 2.18	Bastrop, Texas
734	979.27754	979.278	+ 0.46	Fayetteville, Texas
735	979.34204	979.342	− 0.04	Grand Bay, Alabama
736	979.33831	979.338	− 0.31	Alabama Port, Alabama
737	979.34161	979.342	+ 0.93	Spring Hill, Alabama
739	979.40455	979.405	+ 0.45	Calvert, Alabama
740	979.44635	979.445	− 1.35	Yarbo, Alabama
741	979.47253	979.472	− 0.53	Bolinger, Alabama
742	979.44902	979.450	+ 0.98	Salipta, Alabama
743	979.42678	979.430	+ 3.22	Salt Creek, Alabama
744	979.44429	979.443	− 1.29	Allen, Alabama
745	979.47623	979.476	− 0.23	Sand Flat, Alabama
746	979.50308	979.503	− 0.08	Campbell, Alabama
748	979.43358	979.434	+ 0.42	Claiborne, Alabama
749	979.40901	979.409	− 0.01	Megargel, Alabama
750	979.37521	979.376	+ 0.79	Bay Minnette, Alabama
751	979.38408	979.384	− 0.08	Robinsonville, Alabama
752	979.37612	979.377	+ 0.88	Stockton, Alabama
753	979.34553	979.346	+ 0.47	Fairhope, Alabama
755	979.36664	979.368	+ 1.36	Muscogee, Alabama
757	979.10633	979.105	− 1.33×10^{-3}	Fort Stockton, Texas
883	979.34095	979.341	+ 0.05	Blountstown, Florida
884	979.34421	979.342	− 2.21	Sink Creek, Florida
885	979.38606	979.389	+ 2.94	Mumford, Florida
886	979.40557	979.405	− 0.57	Dothan, Alabama
887	979.37842	979.377	− 1.42	Bonifay, Florida
890	979.38133	979.377	− 4.33	Crestview, Florida
893	979.43461	979.434	− 0.61	Gantt, Alabama
894	979.43274	979.433	+ 0.26	Rome, Alabama

TABLE II—*Continued*

Station	g_0+kS_i	g_i	p_i	*Station Location*
895	979.39916	979.397	− 2.16	Stateline, Alabama
896	979.42092	979.420	− 0.92	Miller Well, Alabama
897	979.44936	979.450	+ 0.64	Garrett Well, Alabama
901	979.45902	979.459	− 0.02	Troy, Alabama
902	979.46403	979.462	− 2.03	Glenwood, Alabama
903	979.45297	979.453	+ 0.03	Elba, Alabama
976	979.82794	979.826	− 1.94	Wellington, Kansas
977	979.64452	979.645	+ 0.48	Caney, Oklahoma
978	979.63053	979.630	− 0.53	Tushka, Oklahoma
979	979.61704	979.616	− 1.04	Dandridge, Oklahoma
980	979.61047	979.610	− 0.47	Atoka, Oklahoma
981	979.65150	979.652	+ 0.50	Bogey Depot, Oklahoma
982	979.65278	979.651	− 1.78	Voca, Oklahoma
984	979.61864	979.619	$+ 0.36\times10^{-3}$	Matoy, Oklahoma
985	979.61858	979.618	− 0.58	Banty, Oklahoma
986	979.63929	979.639	− 0.29	Pritchard, Oklahoma
987	979.64201	979.641	− 1.01	Armstrong, Oklahoma
988	979.65340	979.651	− 2.40	Caddo, Oklahoma
989	979.64085	979.641	+ 0.15	Cobb, Oklahoma
990	979.66826	979.668	− 0.26	Kenefick, Oklahoma
991	979.49011	979.488	− 2.11	Kerens, Texas
996	979.27081	979.270	− 0.81	San Angelo, Texas
997	979.17058	979.170	− 0.58	Big Lake, Texas
1101	980.78620	980.784	− 2.20	Devils Lake, North Dakota
1102	980.81115	980.810	− 1.15	Rugby, North Dakota
1103	980.78263	980.782	− 0.63	Minot, North Dakota
1114	979.55139	979.553	+ 1.61	Lake Providence, Louisiana
1122	979.55816	979.557	− 1.16	Serepta, Louisiana
33	980.94942	980.945	− 4.42	Moosejaw, Saskatchewan
34	980.87307	980.870	− 3.07	Medicine Hat, Alberta
76	980.85696	980.860	+ 3.04	Estevan, Saskatchewan
80	980.98948	980.993	+ 3.52	Elbow, Saskatchewan
81	980.88129	980.882	+ 0.71	Swift Current, Saskatchewan
112	980.99551	980.999	+ 3.49	Kindersley, Saskatchewan

CONCLUSIONS

The results of three adjustments to pendulum stations for the dates August 10, 1940, February 1, 1942, and April 2, 1943, are shown in Table III. The number of pendulum stations used in the last adjustment was approximately double the number used in the first adjustment, whereas, the total gravity range involved more than quadrupled.

TABLE III

RESULTS OF THREE SUCCESSIVE ADJUSTMENTS TO PENDULUM STATIONS

Date	8–10–40	2–1–42	4–2–43
No. Pend. Sta. Used	53	81	100
Gravity range	415.39×10^{-3}	1729.60×10^{-3}	1913.70×10^{-3}
k	0.084382×10^{-3}	0.08463×10^{-3}	0.084673×10^{-3}
g_0	979.33668	979.3360569	979.3361539
ϵ_s	1.1931×10^{-3}	1.0803×10^{-3}	1.2046×10^{-3}
ϵ_h	0.0001×10^{-3}	0.00003×10^{-3}	0.00002×10^{-3}
ϵ_0	0.23036×10^{-3}	0.134×10^{-3}	0.135×10^{-3}

It will be noted that the standard error, ϵ_s, changed very little in the several solutions. This error was obtained from the residuals, ρ_i, and includes errors in the gravity meter measurements as well as errors in the pendulum measurements. The magnitude of the standard error is slightly in excess of 1 milligal and is probably dominated by the errors in the pendulum determinations. The most serious errors anticipated in the gravity meter work are cumulative in type and of the order of 0.25 milligal, maximum, for the stations involved. The probable error in measurement of the earlier pendulum stations is of the order of 1 milligal.[7] The error in the later pendulum measurements is somewhat less than 1 milligal.[8]

Another type of error enters into the pendulum determinations in that the U. S. Coast and Geodetic Survey has standardized its pendulums at several different base stations in Washington, D. C., during the last several years. Since some Canadian pendulum stations have been used in this study, possible errors in the relative pendulum ties between Washington and Ottawa would also be expected to contribute to the standard error.

The probable error, ϵ_k, of the constant of the gravity meter has become less as the number of pendulum stations and gravity range have increased. The adjustment of April 2, 1943, gave an error in the gravity meter constant that is equivalent to 0.024%.

Since the selection of the starting point is arbitrary, the error in g_0 applies to all stations. The value of g_0 is slightly in excess of 0.1 milligal for the later adjustments.

The pendulum stations employed in the solution of April 2, 1943, are adequate in accuracy for the calibration of the gravity meters used, because the error of the constant multiplied by the reading range of the instruments (1000 scale divisions) gives a figure that is of the same order of magnitude as the reading errors.

The data examined shows that the gravity meter may be used to augment or extend networks of gravity pendulum stations over rather wide areas without impairment of accuracy.

Quality in bench marks established by the gravity meter can be improved by:

[7] Hayford and Bowie, *Special Publication No. 10*, U. S. Coast and Geodetic Survey, p. 87 (1910), and A. H. Miller, *Publications of the Dominion Observatory*, Vol. VIII, No. 9, p. 251 (1929).

[8] C. L. Garner, *Trans. Am. Geophysical Union, Part II*, pps. 184–186 (1940).

1. The setting of permanent markers in addition to the written descriptions and sketches used heretofore.
2. The use of a faster mode of travel, since lapsed time is a strong contributor to cumulative errors.
3. The use of stronger ties than the looping method provides. Primary traverses may be employed for control whereas the looping method is sufficiently accurate for most purposes.

ACKNOWLEDGMENT

We wish to acknowledge the kindness of Mr. V. J. Meyer of the Mott-Smith Corporation for permitting the publication of these data.

DISCUSSION

The Coast and Geodetic Survey is planning, when circumstances permit, to use gravity meters freely for the determination of g. This innovation will not mean the abandonment of pendulum determinations of g, but the two methods should be closely coordinated; hence the number and location of new pendulum stations will be profoundly affected by the use of gravity meters.

The problems treated by the authors will then certainly arise in connection with the work of the Coast and Geodetic Survey, and it is therefore encouraging to know that they have already been considered and at least partially solved.

The residuals at pendulum stations from the adjustment shown in Table II of the article are in general about what previous experience has led us to expect, although there are some unusually large ones. These large residuals point to stations where the pendulum and gravity meter observations might both be profitably reexamined critically and where early redeterminations of g with the pendulum might profitably be undertaken, unless the discrepancy can otherwise be explained and removed.

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FAULT LOCATION BY ELECTRICAL PROSPECTING —AN EXAMPLE*

PAUL F. HAWLEY†

ABSTRACT

Electrical resistivity surveys were run in an area near Campbell, Hunt County, Texas, across a known fault of the Mexia system. Lateral inhomogeneity of earth resistivity was investigated by employing constant-depth surveys, using the Wenner configuration with 1000-foot spacing between adjacent electrodes. Five depth surveys were made using the Wenner configuration at electrode spacings up to 4000 feet. These depth surveys were interpreted using 3-layer curves interpolated from the Wetzel-McMurry data. The interpretations checked reasonably well against resistivity logs in two 350-foot core holes in the region. The constant-depth profiles cannot be said to have definitely indicated the presence of the fault, but a thin high resistance bed participating in the faulting was clearly delineated by the depth surveys and could be used to locate the fault.

This paper presents the results obtained by an experimental electrical surveying crew of the joint laboratories of the Stanolind Oil and Gas Company and the Western Geophysical Company, during the months of May and June, 1938. It was the purpose of the work reported to check the use of the resistivity method of electrical prospecting as a means of locating faults. Accordingly, the site of the survey was set in the region around the little town of Campbell, Hunt County, Texas, a short distance to the northeast of Greenville, Texas, in the northeast part of the state. (See Fig. 1.) A few miles west of Campbell is a known fault of the prominent fault zone of East Texas,[1,2] which at this point strikes slightly east of north. Data in several wells indicate that this is a normal fault with the upthrown side to the southeast with a vertical displacement of over 400 feet, and a hade of approximately 45°. It is known that the faulting exists close to the surface, although the strike cannot be traced on the surface. The beds at or near the surface to the east of the fault comprise a considerable thickness of blue clay overlying the Nacatoch sandstone of Cretaceous age, which in some places in the area surveyed outcrops on both sides

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[1] Lahee, "Mexia and Tehuacona Fault Zones," in *Structure of Typical Oil Fields*, A.A.P.G., p. 306, (1929).

[2] *Geologic Map of Texas*, U.S.G.S. (1937).

of the fault, the regional dip being to the southeast. Below the Nacatoch sandstone lies a bed of blue shale. An approximate location of the fault strike based on wells intersecting the fault is given in Fig. 1.

Previous work in other areas had indicated that the ordinary resistivity method of prospecting using the Wenner configuration gave indications of only relatively shallow beds. This has been well established theoretically by the curves prepared by Wetzel and McMurry,[3] which in turn checked the earlier theoretical work of Hummel.[4] Since detailed analysis of resistivity as a function of depth did

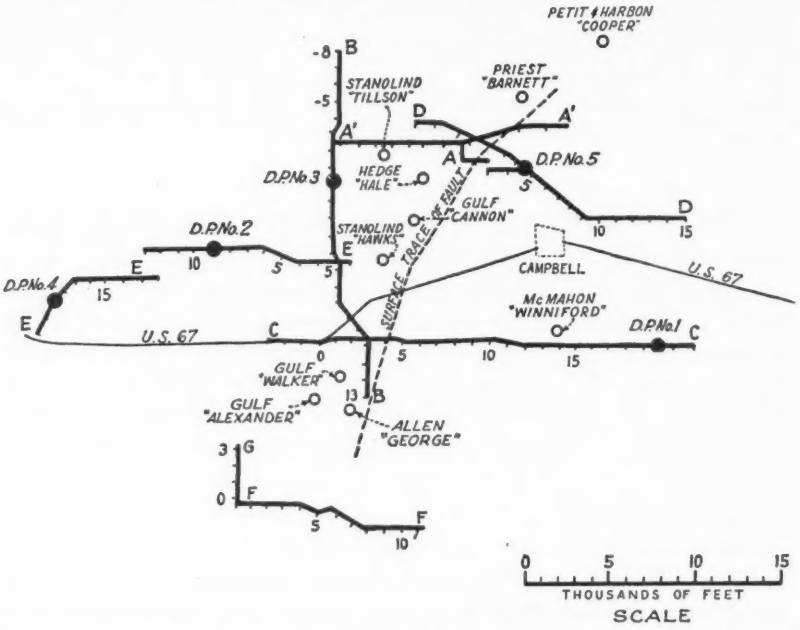


FIG. 1. Map of Campbell prospect, Hunt Co., Texas, showing location of survey stations, constant depth traverses, and probable strike of fault.

not appear possible, the thought naturally arose that although this electrical method apparently had little promise in geophysical exploration for structure at depths greater than about a thousand feet, the method might be applicable for the determination of fairly shallow lateral changes in average earth resistivity such, for example, as could be occasioned by a fault extending to a region near the surface. In

[3] W. W. Wetzel and H. V. McMurry, GEOPHYSICS, Vol. II, No. 4, p. 329 (1937).
[4] J. N. Hummel, *Zeits. für Geoph.*, Vol. 5, p. 89 (1929).

such case beds of considerably different resistivity conceivably might be abutted at depths at which sufficient resolving power might be obtained.

The first line of attack, therefore, was to survey the region using a constant electrode spacing, moving the configuration after each observation. This type of survey is called a constant-depth survey. It is apparent that an electrode spacing should be used which is sufficiently great to give a fair resolving power at the depth of interest and to minimize the effect of local changes in resistance near the surface. On the other hand, there is an economic limit on the maximum electrode spacing which can be used if any appreciable amount of traverse is to be covered each day. In this case, the survey truck had been equipped with cable sufficient to allow electrode spacing of 4000 feet when using the Wenner configuration, that is, maximum spacing between the outer electrodes of 12,000 feet. After making several trial runs at different spacings it was tentatively decided to use a Wenner configuration with spacing of a thousand feet between adjacent electrodes. This spacing was maintained in all of the constant depth-profiles to be presented.

Theoretically, the maximum resolving power should be obtained when running a constant depth survey at right angles to the strike of a fault. However, in this experimental program it was not considered that the expense and trouble involved in obtaining permits across cultivated fields justified this program and accordingly the constant depth profiles were run along the country roads available in the region. In all, eight constant-depth profiles were made along paths which have been plotted in Fig. 1, totalling approximately 117,000 feet. Observations were made every 100 feet along the traverses. Certain portions of the profiles were checked using electrode spacings of 100, 300, 600 and 2000 feet.

The equipment used in making the surveys was conventional in general design. A gasoline motor driven 150 volt d.c. generator was used as the current source, permitting currents of the order of 10 amperes to be employed. Porous pot non-polarizing electrodes were used for the potential terminals and the potential was determined potentiometrically using a Leeds and Northrup potentiometer and a galvanometer with a sensitivity of $\frac{1}{8}$ microampere per scale division, the final balance being determined with a magnifying glass. In order to eliminate the effect of earth currents from the readings, the current was reversed periodically and readings were made of the total differ-

ence of potential. Several check readings were made at each station with a time interval between readings determined by the ability of the observer to carry out the mechanical operations. It might be mentioned in passing that it was found that in the range of currents used the response of the earth was entirely linear, i.e., Ohm's law was followed, so that it was not necessary to maintain the current at a precise predetermined value throughout the survey. With the equipment available it was possible to duplicate results at the same station from day to day with an average variation of not over 2%. Of course, this does not take into effect any marked changes in the surface conductivity, which affects the readings considerably, particularly since the surface conductivity was high. An example of this is found in the uniformly low readings on Traverse A, made after three days of heavy rainfall.

It might be mentioned also that in order to obtain rapidity of operation, the cables used were made up in 4000 foot sections with plugs at the ends and every 100 feet along the line. Enough spare cable was available so that by the use of two extra men with a pick-up truck equipped with reels it was possible to pick up cable behind the party and lay it ahead of the party so that the men at the electrodes merely had to march ahead 100 feet between readings, plant the electrodes and plug into the appropriate cable. Use of this equipment increased the traverse surveyed per day considerably.

In order to interpret the results of constant depth surveys, recourse is usually made to a theoretical analysis of variation in apparent resistivity as a function of the distance from a plane of contact between two materials of different resistivity which are assumed to be homogeneous and infinitely thick. If the contact plane is vertical the variation can be easily computed. A series of curves showing the apparent resistivity as a function of distance from the contact plane has been given by Tagg.[5] Roughly speaking, these curves are approximately as shown in Fig. 2. In general these curves are characterized by certain rises and drops forming what might be termed a "lazy W" figure.

In the survey under question such a fault pattern could not be consistently observed from profile to profile in a manner which would check with the known geology of the region. On certain of the profiles patterns were obtained which appear clearly to indicate the position of the fault, but when additional parallel profiles were run the patterns

[5] G. F. Tagg., *Geophysical Prospecting*, 1934, A.I.M.E., p. 135.

were so indistinct that no reliance could be placed upon the interpretation. Some of this difficulty undoubtedly was due to the fact, which will be developed later in this paper, that much of the material in contact at the fault was not widely different in resistivity. Another fact was that the high resistance bed in the region (the Nacatoch sand) outcropped in places to the east and west of the fault giving an additional disturbance on the profiles. Finally, the fault plane was known not to be vertical but inclined at an angle very roughly 45° to the vertical.

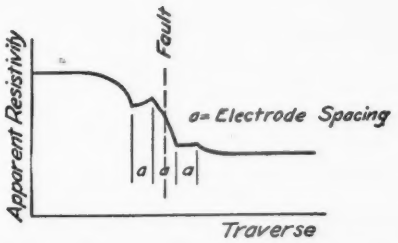


FIG. 2. Typical theoretical fault pattern, vertical fault.

The patterns centering at station 9000 feet on traverse B and at approximately station 1500 feet on traverse C appear to be the best indications of a fault, in so far as checking with the known geology of the region is concerned. (See Fig. 3.) Weak fault patterns appear on traverses A (station 4500 feet), A′ (station 5800 feet) and D (station 500 feet). (See Fig. 4.) The difficulty in employing these fault patterns on traverses A, A′ and D is that the difference between maxima and minima is so small. Thus, for example, one would assume with equal correctness that there is a fault pattern at station 4500 feet on traverse B which, as far as is known, does not correlate with any subsurface discontinuities. It is interesting to note that the possible fault pattern at station 18,000 feet on traverse C and that at station 3600 feet on traverse D appear to outline a fault parallel to the main fault. There is, however, only meager information from geological and other geophysical sources on this point.

An outstanding feature of traverses C and D is the outcrop of the high resistivity Nacatoch sandstone, producing the double humped feature between stations 7000 and 11,000 on traverse C and stations 6000 and 10,000 feet on traverse D. This prominent feature leads to some confusion in the interpretation of the curves. This type of feature with the very sharp changes should theoretically be associated

with a well defined interface between the high resistance bed and the low resistance bed. It is interesting to note that while this was true on traverses C and D where the contact could be determined visually,

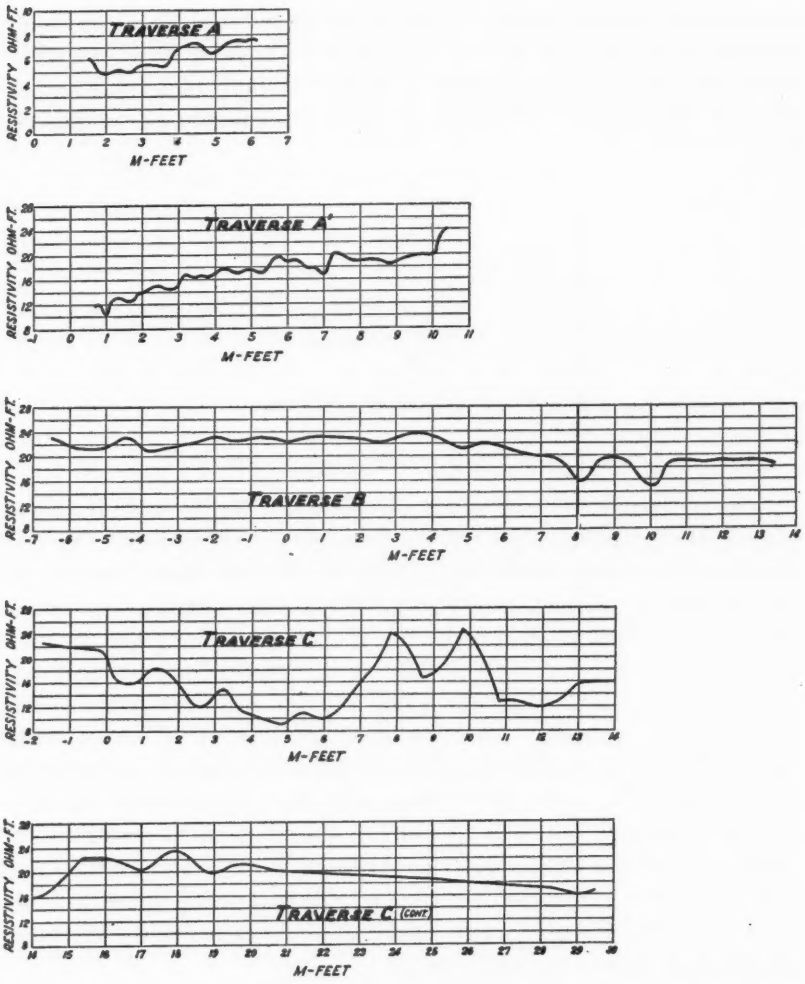


FIG. 3. Constant-depth profiles, traverses A to C.

the contact was entirely unobvious on traverse E which, it is to be noted, contains no such sharp feature at the point of outcrop of the Nacatoch which must, of course, lie somewhere between stations 12,000 and 16,000 on traverse E.

Two depth profiles which had been made appeared to indicate that a more successful determination of the fault might be obtained if depth profiles were used instead of constant depth profiles. In this paper a depth profile is defined as a determination of the apparent resistivity using the Wenner configuration but moving the elec-

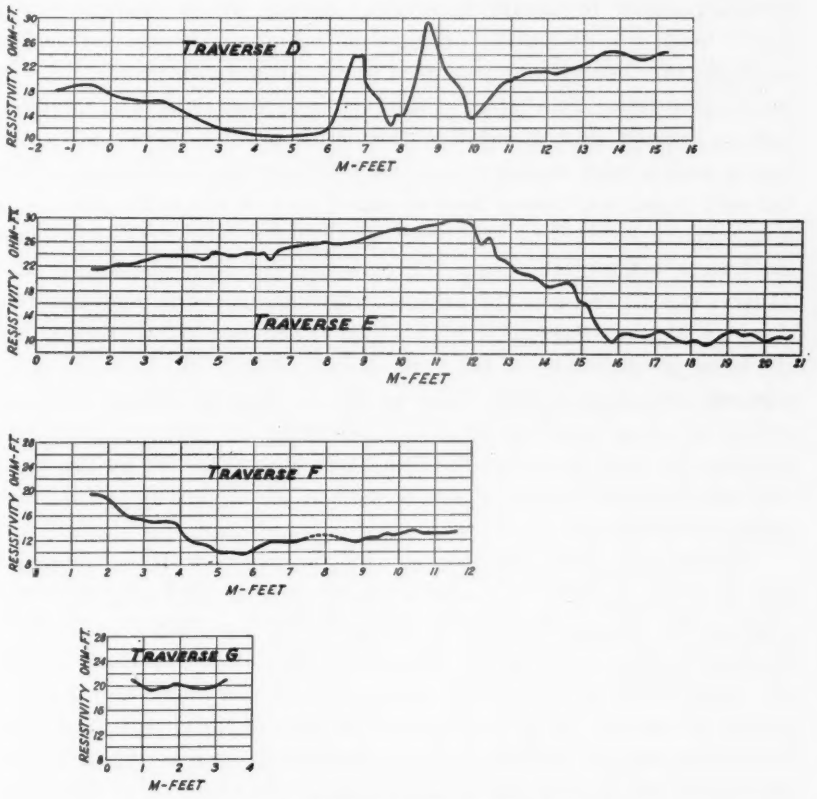


FIG. 4. Constant-depth profiles, traverses D to G.

trodes outwardly and symmetrically with respect to a fixed center point after each observation, so that the resistivity is determined as a function of electrode separation. Five depth profiles were accordingly made at points which are marked on Fig. 1 as D.P. No. 1 to D.P. No. 5 (Fig. 5). Interpretation of these depth profiles was made on the basis of the Wetzel-McMurry curves. The original curves were not directly applicable since the data were solved only for certain spe-

cific ratios of the depths to the various beds and the variation in resistivity between the beds. Accordingly, it was necessary to interpolate between the values given, in order to produce curves more nearly matching the experimental determinations.

It was found that the Wetzel-McMurry system was a powerful means of analysis of the curves (Fig. 5). Without particular difficulty it was possible to obtain theoretical curves which checked fairly closely with the observed variation of the apparent resistivity. For example, the theoretical curve used to interpret depth profile No. 1 is shown as a dashed line superimposed on the actual data. The interpretations showed that in most of the depth profiles there were three layers with a high resistance bed of relatively small thickness lying between upper and lower beds of much greater thickness and much lower resistance. It is to be noted that since the interpretation curves used were interpolated from the curves given by Wetzel and McMurry, the accuracy of the original was obviously not maintainable. Again, since the lithological column near the surface should be roughly the same on both sides of the fault, it was attempted to use the same curve in all interpretations so far as this use did not violate the usual requirements of handling data. The difference in appearance of depth profiles Nos. 4 and 5 from the first three is explainable on the basis that the Nacatoch sand was not present in the section logged at these points. (See Fig. 7.)

Fortunately, it was possible to check the results of two of the depth surveys with shallow vertical resistivity logs. A shot-hole drill was used to drill 350 foot holes at the center of depth profiles Nos. 1 and 2. Resistivity logs were made in these holes using an electrode separation of 4 feet 8 inches between the two potential electrodes and 6 feet 7 inches between the lower potential electrode and the current electrode. These two logs are shown in Fig. 6. In hole No. 1 it is apparent that the resistivity to a depth of 125 feet is of the order of 12 ohm feet. This is a yellow-gray clay followed by a blue clay. There is a thin bed of gray sandy clay or sandstone at a depth of approximately 130 feet with a resistivity of a little over 60 ohm feet and there is a pronounced high resistance sandstone bed between approximately 170 feet and 205 feet with a maximum resistivity of 290 ohm feet. This bed is the Nacatoch sandstone. Below this depth the resistivity is roughly of the order of 10 to 15 ohm feet and from the driller's log appears to be blue shale and gray clay. In the second hole the same features are present except that the resistivity of the upper high resistance bed is greater

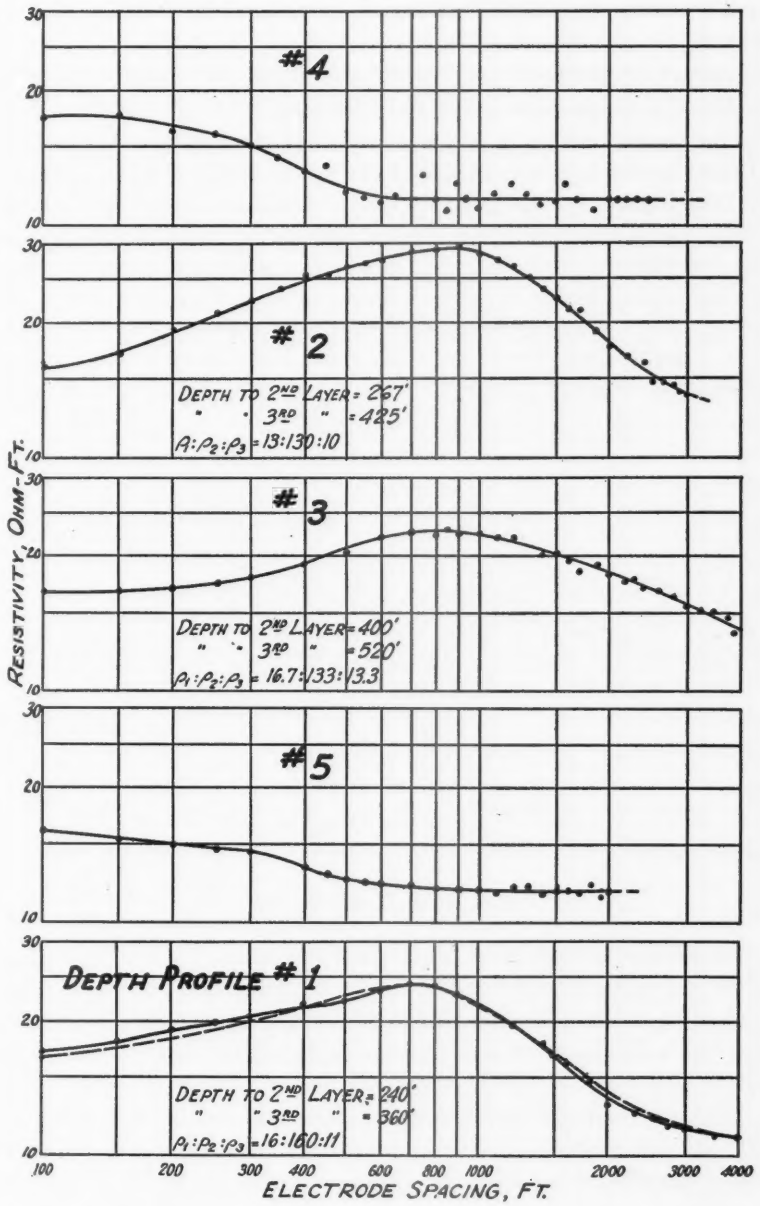


FIG. 5. Depth profiles, arranged in order, from west (top) to east (bottom). The dashed line of Profile No. 1 is the theoretical curve used in the interpretation.

and the overall high resistance region has increased about 20 feet in thickness.

Comparing the results of the depth profile No. 1 and the log of hole No. 1, it is apparent that the thickness of the high resistance beds is of the right order of magnitude and that the depth to the second and third layers is in general too great by the order of 50 to 100 feet. This is probably due to the fact that the ratio of the resistance of the top bed to that of the second was lower in the case of the derived Wetzel-McMurry curve used than that found in the actual well log.

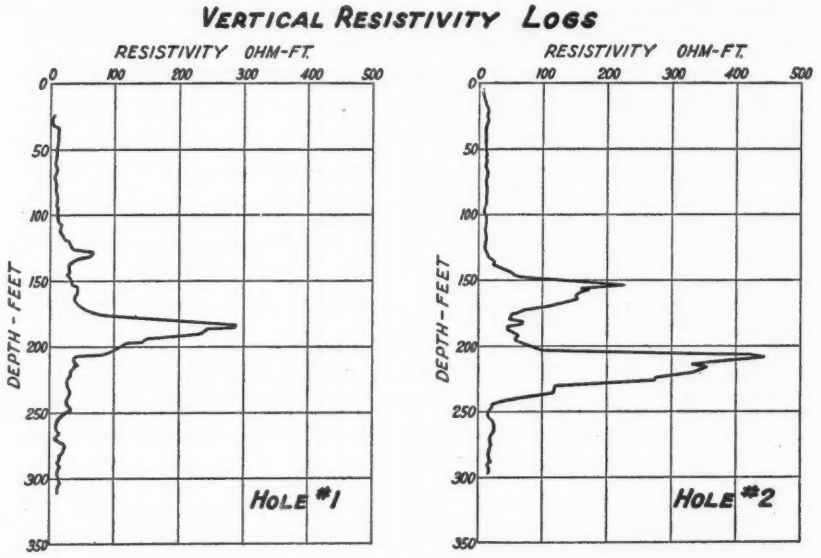


FIG. 6. Vertical resistivity logs.

In comparing the results of depth profile No. 2 with the log of hole No. 2, the same general conclusions are found. It is apparent that the depth profiles obtained to a total electrode spacing of 3000 feet check the variation in resistivity to a depth of the order of 300 to 350 feet.

This may be explained as follows: In depth profiles 1, 2 and 3 the apparent resistivity is increasing up to the order of 700 to 1000 feet spacing between electrodes. An interpretation based on the data up to this distance would indicate a two layer situation in which the lower bed was of higher resistance than the top bed. It is not until the apparent resistivity begins to decrease that one realizes the presence of the

third bed which in this case is the low resistance blue shale below the Nacatoch sandstone. Therefore unless one extended the survey to approximately 2000 feet one would not have enough data to be able to match the appropriate Wetzel-McMurry curve to the observations. On the other hand, it is noted from the vertical resistivity logs at holes 1 and 2 that the depth to the low resistivity blue shale is not over 250 feet. Consequently the conclusion immediately arises that the curves of apparent resistivity against electrode spacing up to a spacing of at least 700 feet between electrodes do not reveal the presence of a bed much lower in resistance than the Nacatoch lying at a depth less than one-third of this electrode spacing. The conclusion can now be drawn from these curves that the effect of a bed of resistivity differing greatly from those of each side is to produce a broad general change in the curve with no sharp narrow folds. These effects check entirely with the theoretical conclusion obtained by Wetzel-McMurry.[6]

It is also apparent from a perusal of the curves of Fig. 5 that with the possible exception of Curve 4 there are relatively insignificant minor variations in the curves, and certainly from the comparison of the vertical resistivity logs and the depth profiles one cannot correlate such minor variations in the apparent resistivity versus electrode spacing with depth to the interface by a one-to-one correlation of the maximum, minimum or inflection points. This again bears out Wetzel and McMurry.[6]

In passing it might be said that the data as to the relative depth of the high resistance Nacatoch bed in depth profiles Nos. 2 and 3 check roughly the regional dip at Campbell and that this is further checked by the dip determined from the outcrop of the Nacatoch sandstone on Profile C (around the 9000 foot station), and the depth of the Nacatoch in Depth Profile No. 1.

On the basis of nothing but the resistivity surveys themselves it is easy to postulate the existence of a fault striking roughly to the east of north from the intersection of profiles B and C. A crude cross section of the region parallel to profiles C and E is shown in Fig. 7 together with the depth profiles, which have been projected into this plane. A high resistance bed is found to exist in depth profile No. 1 at a depth of 240 feet from the surface. This high resistance bed is found to outcrop at around station 9000 on traverse C after which the apparent resistance rapidly decreases to a low of 10 ohm feet. This resistance gradu-

[6] *Ibid.*, pp. 332–333.

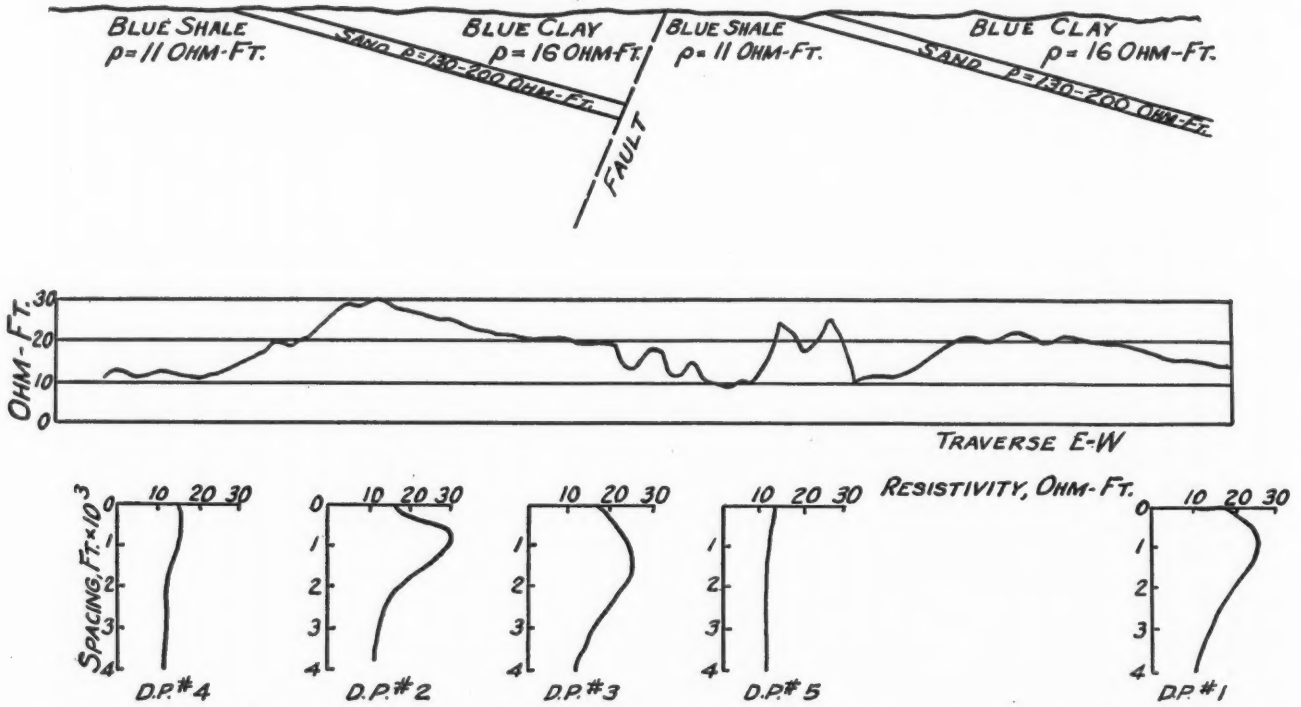


FIG. 7. Approximate E–W cross section across fault, showing typical constant depth profiles, depth profiles, and deduced section. Note: vertical scale greatly exaggerated in cross section.

ally increases in the westward direction with a possible fault pattern centered approximately at station 1400 feet, on traverse C, after which the resistance along this traverse increases to station −1700 feet. Picking up the same trend on traverse E, the resistance steadily increases until it reaches a maximum between stations 10,000 and 12,000 feet indicating the updipping and eventual outcrop of a high resistance bed. The depth profiles 3 and 2 indicate the presence of a high resistance bed, the resistivity of which is the same order as that found in depth profile No. 1, updipping to the northwest. Therefore if the assumption is made that the same high resistivity bed has been picked up on depth profiles 1, 2 and 3, it is apparent that there must be a fault between these points.

In conclusion, the author desires to express his extreme appreciation to the members of the resistivity crew, particularly Messrs. Sexton and Pottorf, for their assistance in the collection and correlation of the data, and to the Stanolind Oil and Gas Company for permission to publish this paper.

ANALYSIS OF GASES BY THE SCATTERING OF ELECTRONS*

S. S. WEST†

ABSTRACT

Methods are described for the analysis of mixtures of hydrocarbon gases by measurement of the probability of scattering of electrons as a function of energy of impinging electron, angle of scattering, or loss of energy during collision. By such means one can determine carbon-hydrogen ratio, proportions of single and multiple carbon-carbon bonds, and concentrations of gases in a mixture.

INTRODUCTION

The analysis of mixtures of gases of which only very small samples are available has become of considerable importance in geophysical exploration in connection with prospecting by measurement of hydrocarbons in soil-air or adsorbed on soil. A method has been developed by Leo Horwitz[1] to separate hydrocarbon gases from air and roughly into groups by selective condensation with dry ice and with liquid nitrogen. The mass-spectrometer has been applied to this problem by Hoover and Washburn[2] and others,[3] so that it has become possible to analyze as little as 1 cu. mm. (N.P.T.) of gas when the mass-spectra of the component gases have been determined. However, the first method provides only a very crude fractionation and no real knowledge of the actual chemical composition of the gases, while the second requires a rather complex apparatus with a heavy electromagnet and a source of at least 1000 volts. It is not generally known that one can escape many of the disadvantages of both methods by utilizing the phenomena of the scattering of electrons in gases, and the following discussion of the possible applications of these phenomena may be of interest to many who have to deal with problems of gas analysis.

When a beam of electrons is projected into a gas at low pressure, many of the electrons are deflected ("scattered") out of the beam by collisions with the molecules of the gas. The collision is called "inelastic" if the scattered electron loses energy to the molecule and

* Presented at the annual meeting, Fort Worth, Texas, April 1943. Manuscript received March 1943.

† Stanolind Oil and Gas Company, Tulsa, Oklahoma.

[1] Leo Horwitz. Geophysics *4*, 210 (1939).

[2] Herbert Hoover, Jr. and H. W. Washburn. A.I.M.M.E. Tech. Publ. #1205.

[3] J. A. Hipple, Jour. of Applied Physics *13*, 551 (1942).

"elastic" if it does not, by analogy with mechanics. The study of the dependence of the probability of scattering upon the energy of the incident electron and the angle through which it is deflected has greatly increased our knowledge of atomic fields. Researches on this subject began about 1927 and have been summarized up to the spring of 1939 by J. H. McMillen.[4] A large part of the theory of these processes is due to N. F. Mott and H. S. W. Massey,[5] who have published their results in book form.

The probability of scattering of an electron depends upon the atomic and molecular structure of the gas-molecule and upon the following variables which describe the conditions of scattering:

1. Pressure of gas.
2. Loss of energy by electron during collision.
3. Energy of incident electron.
4. Angle of scattering.

When the pressure is reduced to 0.001 mm. Hg or less, the probability that the scattered electron will suffer a second collision is negligible, and the probability of scattering is proportional to pressure. Since this greatly simplifies interpretation of measurements, investigations have almost always used such pressures to insure single collisions. Hence only the last three variables are important. In general, one will wish only one of these quantities to vary, and I shall describe how each depends upon the molecular structure of the scattering gas and to what extent one can determine concentrations of gases in a mixture from such dependence. Hydrocarbon gases will be chiefly considered, since the major application of these methods concerns them.

A. ENERGY OF INCIDENT ELECTRONS

Scattering coefficients for elastic collisions between electrons and molecules of methane, acetylene, and ethylene have been measured by Hughes and McMillen[6] for incident electron energies between 10 and 100 electron-volts at scattering angles between 10 and 150 degrees (and for higher energies in certain cases.)

The apparatus used was essentially that shown in Fig. 1. It consists of two parts, a collision chamber *B* and an analyzing chamber to

[4] J. H. McMillen. Rev. of Modern Physics *11*, 84–110 (1939).

[5] N. F. Mott and H. S. W. Massey. *The Theory of Atomic Collisions* (Oxford University Press, 1933).

[6] A. L. Hughes and J. H. McMillen. Phys. Rev. *44*, 876 (1933).

reject inelastically scattered electrons. Electrons are emitted from a hot filament F of the gun G, whose two slits collimate the electron beam. An electric field between F and the first slit accelerates the electrons. Electrons scattered from the region C pass through slits S_1 and S_2 into the analyzing chamber. The analyzer is of the design of Hughes and Rojansky,[7] in which a radial electric field between two

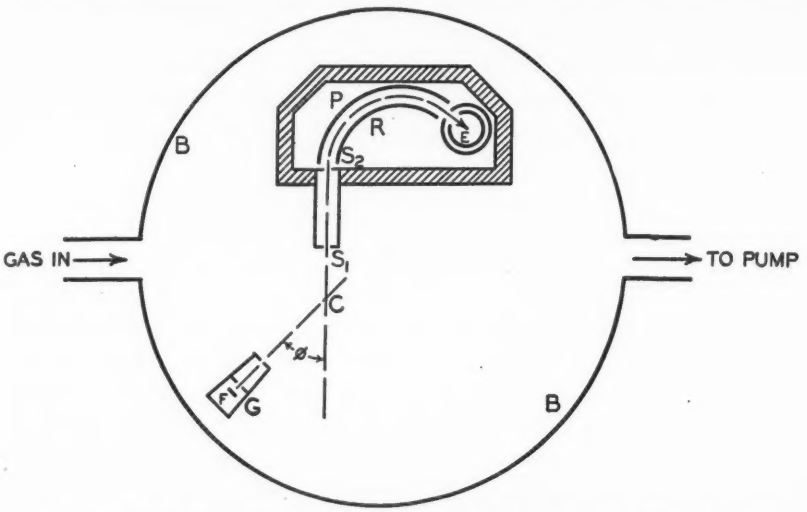


FIG. 1. Section of the apparatus of Hughes and McMillen in a plane parallel to the direction of the electron beam and to the direction of the scattered electrons which are measured. Gas enters the chamber B at the left and is pumped out at the right, the flow being adjusted to maintain a low pressure in B. Electrons emitted from the hot filament F are accelerated through the slits of the gun G. Electrons scattered from the region C through an angle ϕ pass through the slits S_1 and S_2 into an analyzer consisting of the oppositely-charged cylindrical plates P and R. Scattered electrons of a selected energy enter the collecting cup E, the current I_c to which is proportional to the probability of scattering. The long axes of all slits are perpendicular to the plane of the drawing.

coaxial metal cylinders P and R focusses electrons of a chosen energy upon the collecting cup E. Gas is admitted through a tube attached to the scattering chamber to keep the pressure at a constant value near 0.001 mm. Hg.

From the tabulated data of Hughes and McMillen, scattered electron current (in arbitrary units) has been plotted in Fig. 2 against energy of incident electrons (in electron-volts) at a scattering angle of 15°. In Fig. 3 the same variables have been plotted for an angle of 90°,

[7] A. L. Hughes and V. Rojansky. Phys. Rev. *34*, 284 (1929).

and in Fig. 4 is shown total elastically scattered electron current (integrated over the whole angular range from 0 to 180°) as a function of energy of incident electrons. The unit of scattered electron current is arbitrary but is the same for all three sets of curves. It will be seen that each of these curves is characteristic of the molecule producing it and differs a great deal from the other curves obtained at the same scattering angle. This fact can form the basis of a method of analysis of a mixture of hydrocarbon gases.

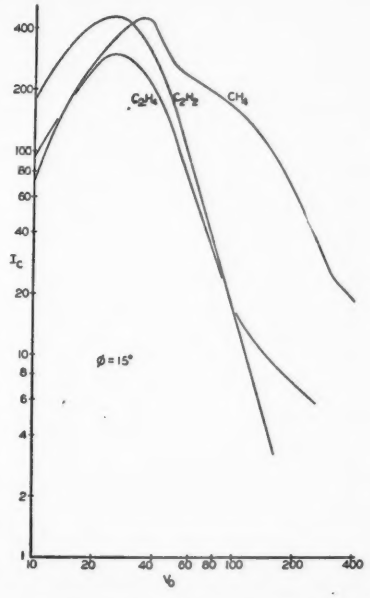


FIG. 2. Scattered electron current I_c (in arbitrary units) as a function of electron energy V_0 (in volts) for electrons scattered elastically through an angle $\phi = 15°$ in methane, acetylene, or ethylene.

Assume a knowledge of the scattering coefficient (probability that an electron will be scattered into unit solid angle at an angle ϕ) over a sufficient range of energies for each of the n kinds of hydrocarbon molecules which are present in the gaseous mixture. Select n values of energy E_j at which the scattering coefficients of the component gases have ratios different from those corresponding to other energies of the group E_j. Let

a_{ij} = scattering coefficient at unit concentration of molecule.
X_i = concentration of molecule.
k_j = observed scattering in mixture at energy E_j

where the index i designates the molecular species and the index j designates the electron energy. Solution of the n simultaneous equations

$$\sum_{i=1}^{n} a_{ij}X_i = k_j \qquad (j = 1, 2, 3, \cdots, n)$$

yields the concentrations X_i of the component gases. Since a complete analysis requires only a knowledge of all *relative* concentrations, these

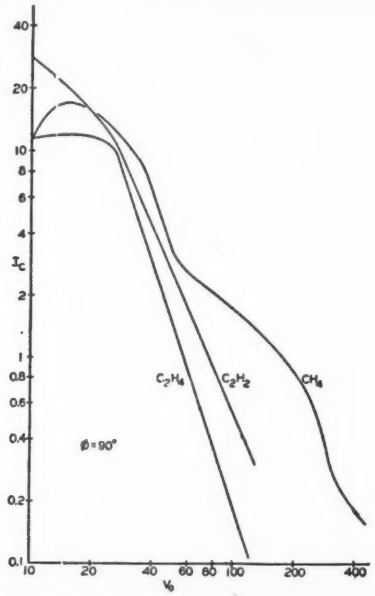


FIG. 3. Scattered electron current I_0 (in arbitrary units) as a function of electron energy V_0 (in volts) for electrons scattered elastically through an angle $\phi = 90°$ in methane, acetylene, or ethylene.

equations can be reduced to $n-1$ equations containing only ratios of scattering coefficients and ratios of concentrations and having the form

$$\sum_{i=1}^{n} \frac{a_{i1}}{a_{11}}\left(1 - \frac{a_{ij}}{a_{i1}}\,\frac{k_1}{k_j}\right)\frac{X_i}{X_j} = 0 \qquad (j = 2, 3, 4, \cdots, n).$$

This process assumes only that scattering from each type of molecule is proportional to its partial pressure in the mixture, which is true when only single collisions can occur. Concentrations are often calculated in the same way in the case of the mass-spectrometer, for which the coefficients denote abundances of ions of various masses.

The method is not limited to the range of energies for which data is given in Figs. 2 to 4, but scattering falls off very rapidly at higher energies, which makes measurement difficult. Neither is it desirable to use scattering angles less than about 10°, because of the difficulty of restricting the beam and the angle of acceptance of the analyzer so that no electrons from the incident beam will enter the analyzer with the scattered electrons.

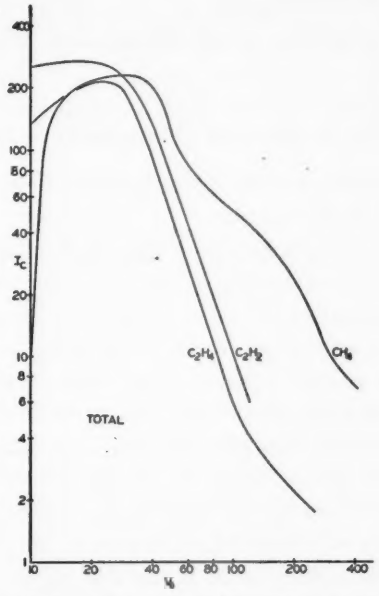


FIG. 4. Total scattered electron current I_0 (in arbitrary units), integrated over all angles, as a function of electron energy V_0 (in volts) for electrons scattered elastically in methane, acetylene, or ethylene.

The method is not limited to elastic scattering. This was discussed only because data were available, and a characteristic function of scattering probability as function of energy of incident electron exists for each molecular species at each value of energy loss of inelastically scattered electrons and for the sum of elastically and inelastically scattered electrons. Any such function or combination of them can be used for the analysis in the manner described above.

The apparatus required for this kind of analysis is relatively simple. It consists of the following units:

1. Scattering chamber and analyzer.

These are enclosed by a vacuum tight shell of metal or glass,

which need be no larger than 5 or 6 inches in its greatest dimension.

2. Vacuum pump.
   Mechanical pump (such as Cenco "Hyvac") plus mercury or oil diffusion pump plus cold trap.
3. Gas supply unit.
   Capillary leak and storage reservoir with necessary stopcocks.
4. Vacuum tube electrometer.
   Circuit according to DuBridge and Brown,[8] Penick,[9] or Roberts.[10]
5. Voltage source.
   A maximum of 200 volts will probably suffice.

The whole assembly will therefore be quite light in weight and will occupy a relatively small volume.

A very interesting application of this method is suggested by Fig. 4, in which is plotted scattering integrated over all angles from 0 to 180°. Here the apparatus can be simplified by making the scattering chamber and analyzer similar to a tetrode radio tube in size and construction. We may permit a pencil of electrons to pass into and out of the scattering space through circular apertures and along the axis of a cylindrical grid. Around this grid we place a second, coaxial grid and around it a coaxial plate. Most of the scattered electrons will pass through the first grid, no matter what their scattering angle, and they may be retarded by an electric field between the grids to permit only elastically scattered electrons to reach the plate. The advantage of this arrangement is not so much its small size or its simplicity as the much larger current to the collector, which permits a less sensitive electrometer to be used. Obviously, all inelastic electrons cannot be excluded from the collector without excluding elastic electrons with a large component of momentum in the axial direction, but for analytical purposes it does no harm to include inelastic electrons in the measured current.

While analysis by variation of scattering probability with energy of incident electrons cannot discriminate as finely as the mass-spectrometer nor determine molecular weight, it is capable of precise analysis of mixtures of a small number of components. In addition, the small-

[8] L. A. DuBridge and Hart Brown. Rev. of Sci. Instr., *4*, 532 (1933).
[9] D. B. Penick. Rev. of Sci. Instr. *6*, 115 (1935).
[10] S. Roberts. Rev. of Sci. Instr. *10*, 181 (1939).

ness and simplicity of the apparatus make it very suitable for the automatic control of chemical processes, a continuous indication or control being obtained with the consumption of only a minute quantity of gas.

B. ANGLE OF SCATTERING

The data of Hughes and McMillen[6] for methane, acetylene and ethylene can be plotted in terms of probability of scattering as function of angle of scattering at constant energy of incident electrons. Fig. 5 shows such curves for an energy of 100 electron-volts. The maxima and minima characteristic of electron diffraction are very evident, and the curves differ enough for one to apply the method of

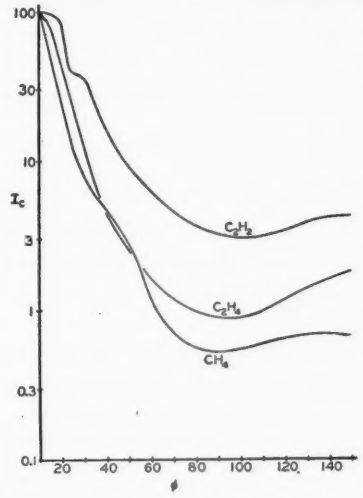


FIG. 5. Scattered electron current I_c (in arbitrary units) as a function of scattering angle ϕ (in degrees) for electrons scattered elastically with an energy of 100 electron-volts. I_c set equal to 100 at $\phi = 10°$ for each curve.

the preceding section to calculate the concentrations of such compounds in a mixture. In this case, we choose n angles (when the mixture contains n components), at each of which the scattering coefficients of the gases differ from one another. The simultaneous equations have the same form as before and are solved in the same manner to obtain the concentrations. Of course, it is not yet known how much difference there will be between scattering curves for members of the same homologous series of hydrocarbons, but it is probable that this will be fairly large because of angular displacement of the diffraction maxima.

The curves do not differ as much in this case as when incident electron energy is the variable, but here it is possible to measure scattering simultaneously at several angles by means of a multiplicity of analyzers or simple collecting cups. This should be of value when automatic control of chemical processes is desired, for one is not forced to introduce a device to sweep the variable quantity (such as energy) cyclically over a certain range or set of discrete values.

C. LOSS OF ENERGY DURING COLLISION

When the angle of scattering and the energy of the incident electron are both fairly large, it is possible to calculate the expected ratio of the probabilities of inelastic and elastic scattering from the molecular structure of the hydrocarbon gas in question. This is done in the following manner.

The formula for the scattering of electrons by bare nuclei is

$$\text{Use } \alpha_1 = (Ze/4m^2v^4)\ \text{cosec}^4\ (\phi/2)$$

where α_1 is the probability that an electron of mass m and velocity v will be scattered into unit solid angle, at an angle ϕ with its original direction, by a nucleus of charge Ze. This formula was derived by Rutherford[11] on the classical particle theory, but wave mechanics lead to precisely the same formula.[12]

On the basis of wave mechanics, Mott[13] derived for the scattering of electrons by electrons initially at rest the formula

$$\alpha_2 = (e^4/m^2v^4)4\ \cos\phi(\text{cosec}^4\ \phi + \sec^4\ \phi - \Phi\ \text{cosec}^2\ \phi\ \sec^2\ \phi)$$

where

$$\Phi = \cos\ [(2\pi e^2/hv)\ \log\ \tan^2\ \phi]$$

and the other quantities have the same significance as in the preceding paragraph. When ϕ is greater than 20° and electron energy greater than 2000 electron-volts, Φ is within 2% of unity and we shall therefore obtain a good approximation by putting $\Phi = 1$.

When the nucleus and stationary electron are part of an atom or molecule, a 2000-volt electron must pass so close to such a scattering center to be deflected through an angle greater than 20° that only very seldom will it be influenced by one of the other scattering centers in

[11] E. Rutherford. Phil Mag. *21*, 669 (1911).
[12] N. F. Mott and H. S. W. Massey. *The Theory of Atomic Collisions*, Chap. III.
[13] N. F. Mott. Proc. Roy. Soc. *A126*, 259 (1930).

the atom. Thus the deflection of the electron is due either to a nucleus or to an atomic electron, but almost never to both. Hence one can calculate the ratio to be expected for a given atom or molecule and compare it with observed data. In this manner the formulas have been verified by Hughes and West[14] for helium and hydrogen.

We can distinguish between scattering by nuclei and scattering by atomic electrons by the fact that electrons lose no energy when they are scattered by nuclei but do lose energy when they are scattered by atomic electrons. In the latter case the energy of the electrons after collision is $V = V_0 \cos^2 \phi$, where V_0 is the energy of the impinging electrons and ϕ is the angle which the path of an electron after collision makes with the path of the impinging electron before collision. If we replace the cylindrical analyzer by a simple retarding field, a plot of collected electron current I_c as function of retarding potential V_1 will have the form of Fig. 6, in which the step I_1 represents elastically

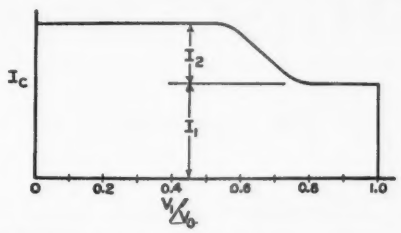


FIG. 6. Scattered electron current I_c for electrons scattered inelastically through a given angle ϕ with energies greater than V_1. Here V_1 is given as a fraction of the energy V_0 of the incident electrons.

scattered electrons and the step I_2 inelastically scattered electrons. Since the atomic electrons are in random motion instead of being at rest, the horizontal portions of the curve are connected by a sloping line instead of a discontinuous step at $V_1 = V_0 \cos \phi$. However, the ratio of the heights of the steps represented by the horizontal portions is still the ratio of the probabilities of inelastic to elastic scattering.

Now consider a gas composed of hydrocarbon molecules, each of which contains n atoms of hydrogen and m atoms of carbon. The hydrogen atom has one valence electron and a nucleus with one unit positive charge, while the carbon atom has four valence electrons and a nucleus with four unit positive charges. Hence, when scattering is caused only by single centers of force, the ratio of inelastically scattered to elastically scattered electrons will be

[14] A. L. Hughes and S. S. West. Phys. Rev. *50*, 320 (1936) and *52*, 43 (1937).

$$\frac{\alpha_2}{\alpha_1} = \frac{nf_2(\phi) + 4mf_2(\phi)}{nf_1(\phi) + 16mf_1(\phi)} = \frac{n + 4m}{n + 16m} \cdot \frac{f_2(\phi)}{f_1(\phi)} = \frac{n/m + 4}{n/m + 16} \cdot F(\phi)$$

where

$$f_1(\phi) = \text{cosec}^4 (\phi/2)$$

and

$$f_2(\phi) = 4 \cos \phi(\text{cosec}^4 \phi + \sec^4 \phi - \text{cosec}^2 \phi \sec^2 \phi)$$

so that

$$F(\phi) = [4 \cos \phi(\text{cosec}^4 \phi + \sec^4 \phi - \text{cosec}^2 \phi \sec^2 \phi)]/\text{cosec}^4 (\phi/2).$$

It has been assumed here that scattering is equally likely for all nuclei and all molecular electrons, which is true under the conditions specifying single-center scattering.

Since the function $F(\phi)$ is known, (for example $F(\pi/4) = 1$), one can calculate the ratio n/m of hydrogen atoms to carbon atoms from the ratio α_2/α_1.

If one writes

$$p = (\alpha_1/\alpha_2)F(\phi),$$

then

$$n/m = (16 - 4p)/(p - 1).$$

Some examples of the use of this formula are given in the following table.

Molecule	*n/m*	*p*
CH_4	4.00	2.50
C_2H_2	1.00	3.40
C_2H_6	3.00	2.71
C_3H_8	2.67	2.80
C_4H_{10}	2.50	2.84
C_8H_{18}	2.25	2.92

Since p approaches a limit with increasing molecular weight for each homologous series of hydrocarbons, the distinction becomes less clear for heavy molecules. Nevertheless, the test is simple and rapid, and it should prove useful in cases where one desires to know the carbon-hydrogen ratio continuously and without the consumption of much gas.

If the gas is a mixture of several kinds of molecules, the observed value of α_2/α_1 will be an average, with the several compounds weighted according to their concentrations. Only in special cases can this

method be used directly for analysis, but it can serve as a check upon the methods described in the preceding sections.

The apparatus required is the same as that described previously, with the substitution for the Hughes and Rojansky analyzer of a pair of slits, between which is a retarding field. The current I_c through these slits to the collecting cup is measured once on each of the plateaus of Fig. 6, and from these measurements one obtains immediately α_2/α_1, since the ratio of the greater current to the lesser is $1+\alpha_2/\alpha_1$. Two collectors at the same scattering angle, one with retarding field and one without, can be used to yield both currents simultaneously, their ratio being indicated by one of the common types of ratio meters.

In discussing Fig. 6, it was pointed out that the sloping portion of the curve is due to the distribution-in-energy of the inelastically scattered electrons, which results from the fact that the atomic electrons are in random motion instead of at rest when the collision occurs. Now if we use the apparatus of Fig. 1 instead of the analyzer with a retarding field, we can measure this distribution-in-energy and obtain a curve like that shown in Fig. 7. Here ordinates represent numbers of

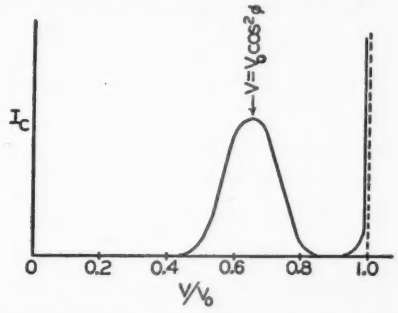


FIG. 7. Scattered electron current I_c as a function of resultant energy V for electrons of initial energy V_0, scattered inelastically through an angle ϕ.

scattered electrons and abscissas the corresponding energies V as fractions of the energy V_0 of the impinging electrons. The maximum occurs at approximately $V=V_0\cos^2\phi$. From the shape of this peak one can calculate the velocity distribution of the molecular electrons, using the conditions of conservation of energy and momentum in the collision. The narrow peak at $V/V_0=1$ represents the elastically scattered electrons.

Jauncey[15] showed that the distribution-in-energy of the scattered

[15] G. E. M. Jauncey. Phys. Rev. *50*, 326 (1936).

electrons has the same form as the distribution-in-component-velocity of the molecular electrons, and the phenomenon has been studied by Hughes and Mann[16] and by Hughes and Starr,[17] who made measurements on helium, nitrogen and methane. Quite recently, Hughes and Enns[18] investigated the distribution of component velocities of electrons in acetylene, ethylene, ethane, and methane, and their data are shown in Fig. 8, where ordinates represent probabilities and abscissas component velocities of molecular electrons. Only the bonding electrons are sufficiently far from the nucleus to influence scattering appreciably.

The average velocities of the bonding electrons in ethylene and acetylene are seen to be substantially identical except for a slight difference in the region of lower velocities, but fast electrons in methane and ethane are considerably fewer than in ethylene and acetylene.

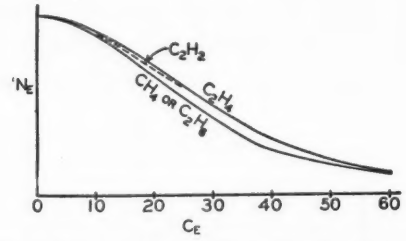


FIG. 8. Probability N_0 that a molecular electron will have the component velocity C_E (in units of 10^7 cm/sec.) in a given direction, for methane, acetylene, ethylene, or ethane. These curves have the same shape as half of the peak in Fig. 7.

Fig. 9 shows the ratios of the ordinates of Fig. 8 as functions of component velocity of molecular electrons. (The ratios were computed from Table I of the paper of Hughes and Enns.[18]) The considerable difference between the average velocity distributions of the bonding electrons provides a means for distinguishing between molecules on the basis of the relative numbers of single, double and triple bonds.

In the simplest approximation, one can assume that there are four kinds of electron bonds in hydrocarbon molecules, these being *H-C*, *C-C*, $C=C$ and $C\equiv C$, each of which will have its characteristic velocity distribution. To obtain the average velocity distribution for a hydrocarbon molecule, one has only to multiply each of the four fun-

[16] A. L. Hughes and M. M. Mann. Phys. Rev. *53*, 50 (1938).
[17] A. L. Hughes and M. A. Starr. Phys. Rev. *55*, 343 (1939).
[18] A. L. Hughes and T. Enns. Phys. Rev. *60*, 345 (1941).

damental distributions by the number of bond electrons of that kind and add.

Coulson and Duncanson[19] have shown theoretically that electron velocities in *H-C* bonds are modified by adjacent bonds in such a way as to make the averages more similar, but the observations of Hughes and Enns show a greater difference than that permitted by the theory.

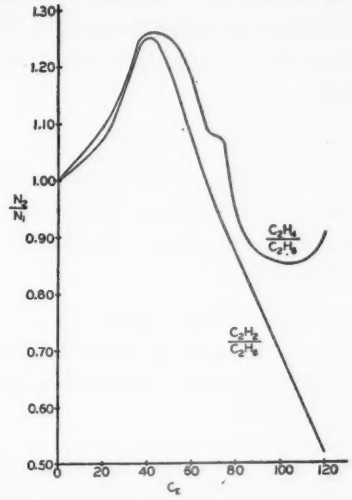


FIG. 9. Ratio of the ordinates of pairs of the curves of Fig. 8 as a function of average component velocity of molecular electrons (in units of 10^7 cm/sec.).

Upon the shape of the velocity-distribution of the molecular electrons one can base a method for identifying unknown hydrocarbon molecules according to the relative numbers of the four types of bonds. Whether it is possible to distinguish directly between the fundamental bonds or only between various structural types of molecules can only be learned by further investigation. In any case, the actual procedure will be to measure the probabilities of inelastic scattering (relative to maximum inelastic scattering) at a number of energies (as in Fig. 7), and apply the method of simultaneous equations which has been discussed. A similar procedure has been suggested by Hughes.[20]

Admittedly, the measurement is difficult, but the difference between curves is not so small that technique could not be refined to permit a fairly precise determination of the concentrations of several

[19] C. A. Coulson and W. E. Duncanson. Proc. Camb. Phil. Soc. *37*, 67 (1941).
[20] A. L. Hughes. Amer. Jour. of Physics, *10*, 63 (1942).

molecular species. The greatest difficulty arises from the fact that the scattered electron current is very small at energies of several thousand electron-volts and is made still smaller by the selection of only those inelastically scattered electrons whose energies lie in a narrow range. However, the situation might be greatly improved by constructing the collecting slit and analyzer to be cylindrically symmetrical with respect to the beam of impinging electrons, instead of accepting only electrons from a small range of azimuthal angle. This demands a different type of focussing in the analyzer, but can probably be done without much difficulty.

CONCLUSION

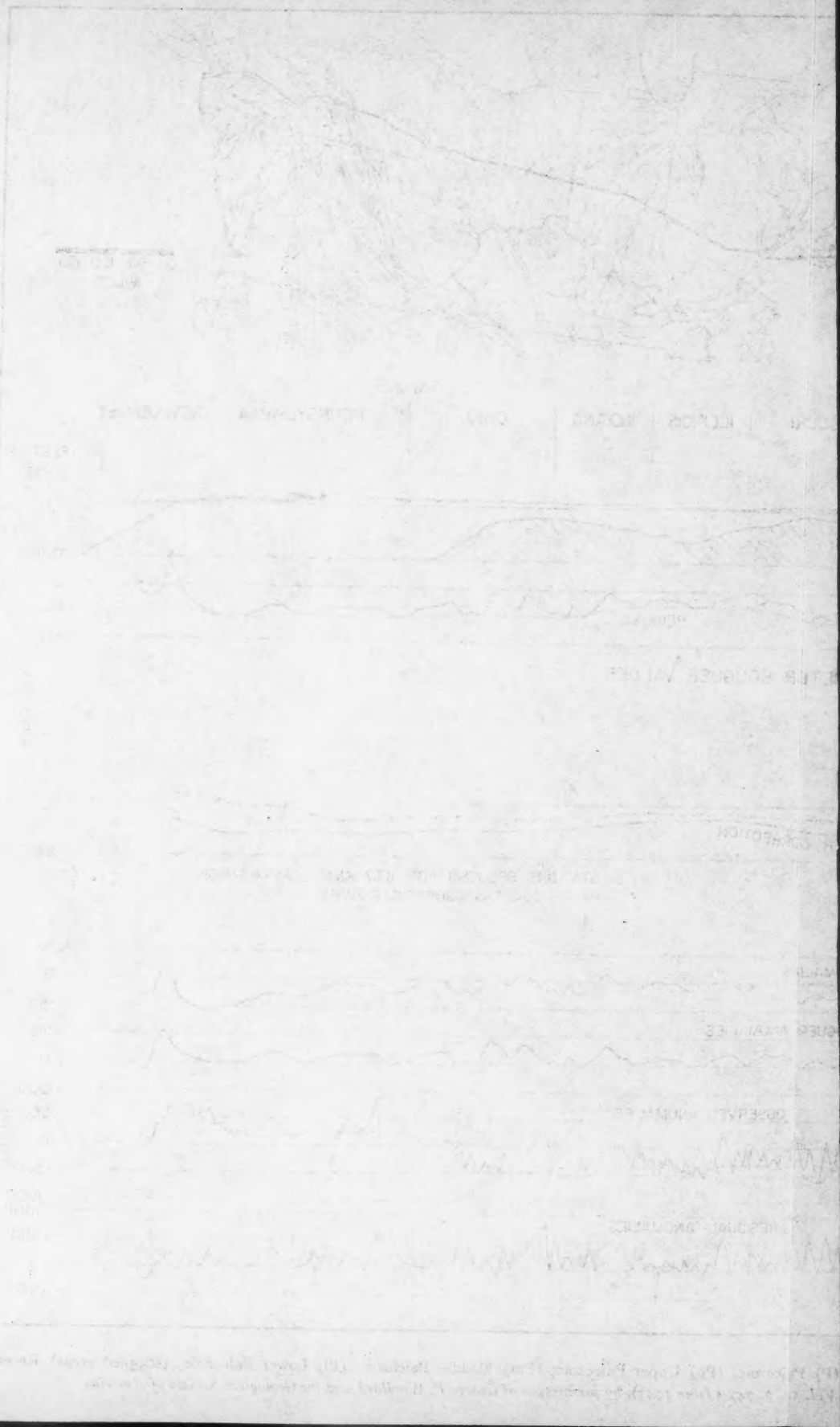
While the methods for the analysis of hydrocarbon gases by means of electron scattering have been discussed with respect to the phenomenon utilized for this purpose, the kinds of information obtained can be classified as follows:

1. Carbon-hydrogen ratio. (Section C)
2. Relative numbers of different types of bonds. (Section C)
3. Concentrations of component gases in a mixture. (Sections A and B)

The carbon-hydrogen ratio can be obtained without any previous knowledge of the composition of the unknown gas. The proportions of the bonds can probably be measured well only for a pure gas or when the component molecules are of known structural classes. The concentrations of the components can be found only when the molecular structure of each is known beforehand. Thus the sequence here is the order in which the methods could be applied most conveniently.

It is obvious that the other methods for the microanalysis of hydrocarbon gases, fractional condensation and mass-spectrometry, can frequently assist electron scattering, but the latter is much better adapted to routine analysis by its simplicity and ease of measurement. While the most direct application is to soil-gas exploration, there is little doubt that use could be found for it in all branches of the petroleum industry. In addition, the methods of Sections A and B can be applied equally well to inorganic gases.

I wish to express my appreciation to the officers of the Stanolind Oil and Gas Company and the Western Geophysical Company for permission to publish this paper.



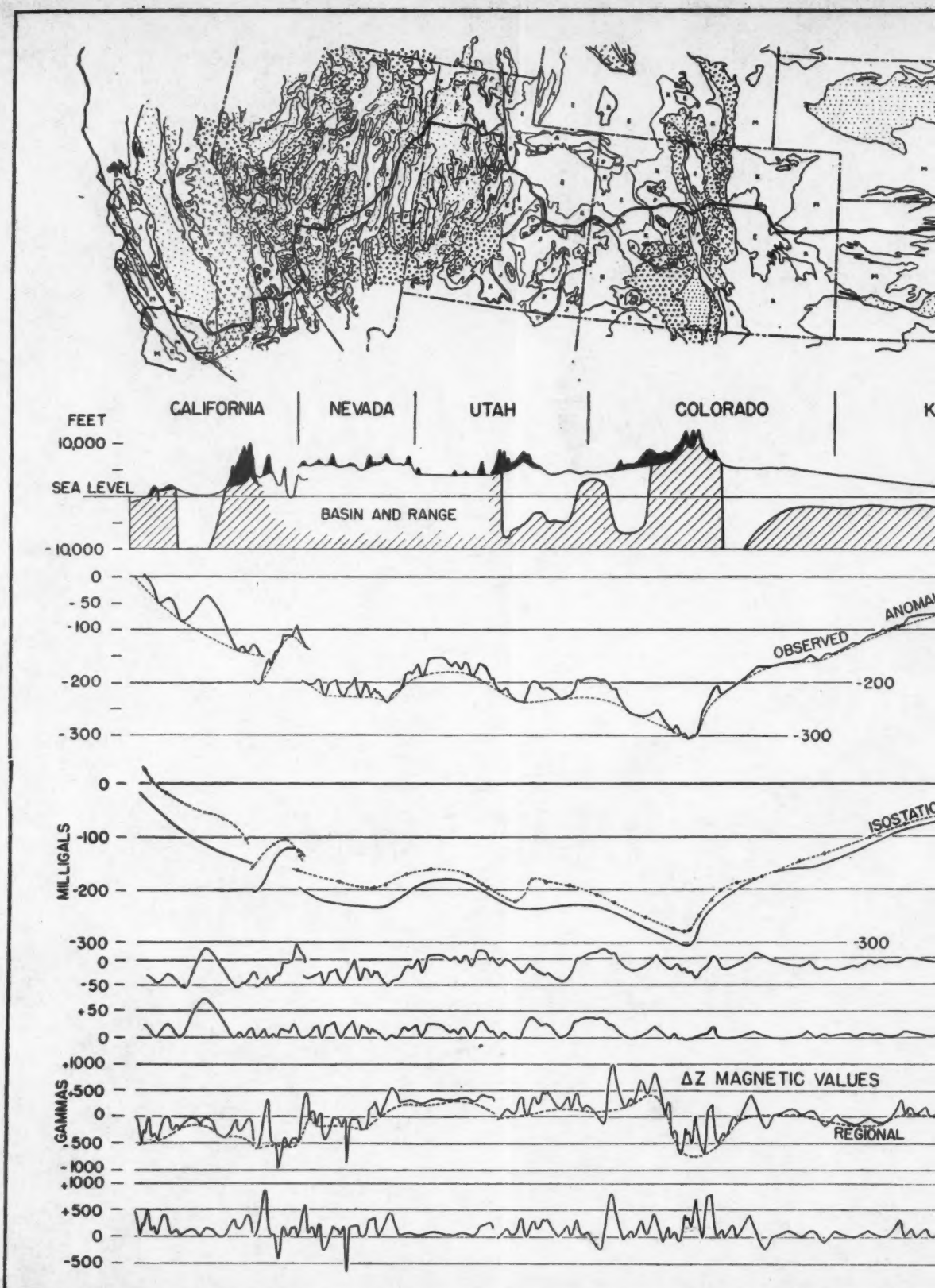
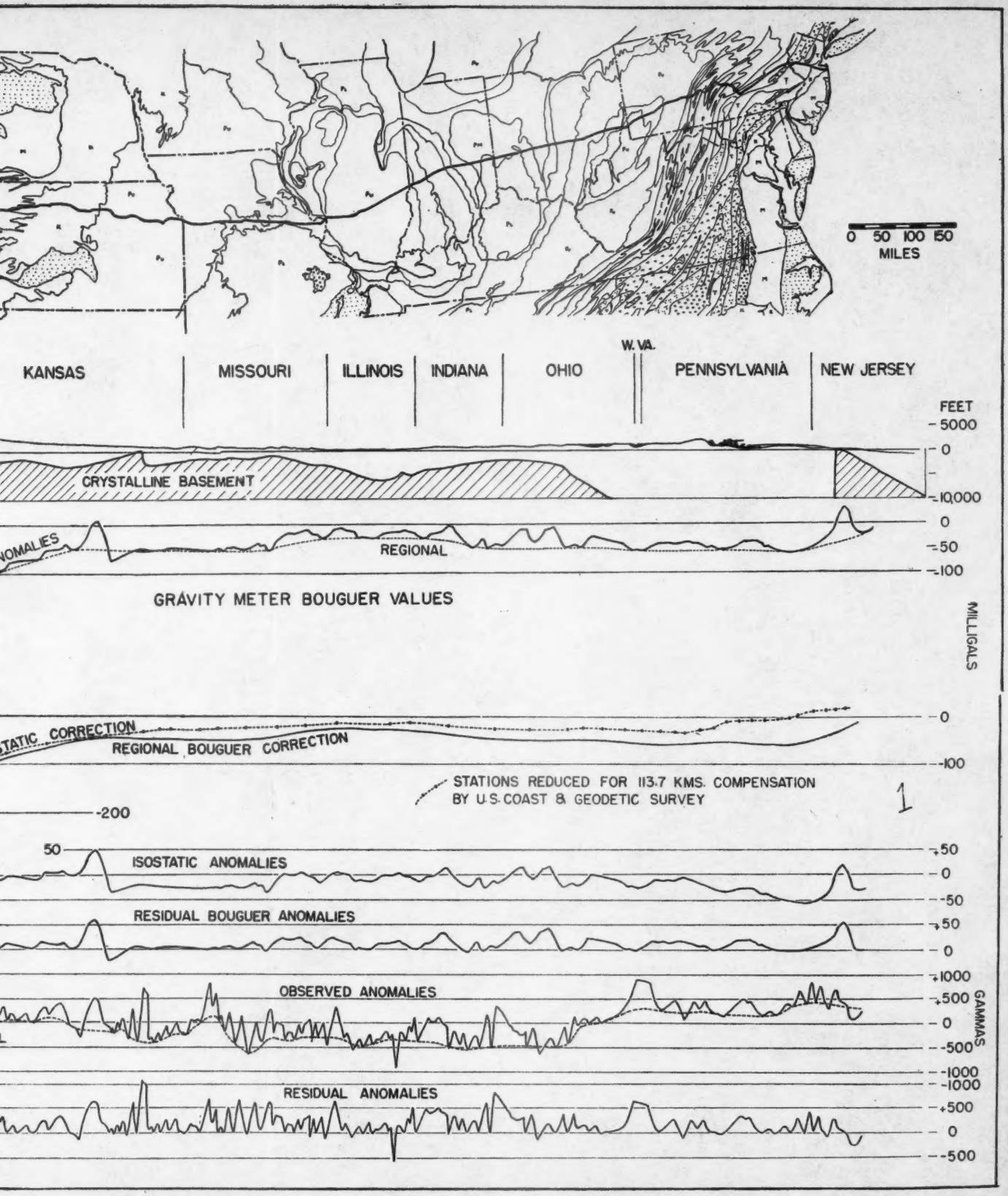


PLATE I. Areal plot and profile of transcontinental gravitational and magnetic traverse. (M) Miocene; (K) Cretaceous; (cross areas) volcanic; ("v" areas) diabase; (crow foot areas) granitic rocks. *Reproduced from the Bulletin of the G*



ous; (J) Jurassic; (T) Triassic; (P) Paleozoic; (Pu) Upper Paleozoic; (Pm) Middle Paleozoic; (Pl) Lower Paleozoic; (stippled areas) Recent;
the Geological Society of America, Vol. 54, p. 747 (June 1943), by permission of George P. Woollard and the Geological Society of America.

REVIEWS

Transcontinental Gravitational and Magnetic Profile of North America and Its Relation to Geologic Structure. George P. Woollard. Bulletin of the Geological Society of America, Vol. 54, Pages 747-790. June 1, 1943.

This paper is the final publication of the results of the transcontinental traverse of gravity and magnetic measurements carried out by Prof. Woollard in the summer of 1940. The first public announcement of the results of this work was given at the Houston meeting of the S.E.G. in 1941, when a paper with substantially the same title was listed to be read by title and an extensive abstract was published in the program of the meeting. A large chart corresponding approximately to Plate 1 of Woollard's present paper was shown at that meeting and was discussed informally, although Prof. Woollard himself was not able to be present.

Probably the most important part of the present report is the quite complete set of charts which now make all of this material available. The over-all picture of the transcontinental traverse is given by Plate 1, which has been reproduced for this review. In addition, there are seven other plates showing results, each of which gives in greater detail a part of the traverse. Each of these seven charts shows (1) the surface geology, (2) a geologic cross-section, (3) an elevation and terrain section, (4) the Bouguer gravity anomaly with a regional curve and (5) a Δz (magnetic) anomaly curve with a regional curve. The seven charts, having a certain amount of overlap which facilitates their continuity, cover the following areas: Plate 3—California and Nevada, Plate 4—Nevada and Utah, Plate 5—Colorado, Plate 6—Kansas, Plate 7—Missouri and Illinois, Plate 8—Indiana and Ohio, Plate 9—Pennsylvania and New Jersey. (Plate 2 gives details of reduction of magnetic base station values.) These plates are all printed as folded inserts and show the location of the individual stations and the magnetic and gravity values at each station. They are on a sufficiently large scale and in sufficient detail so that anyone else wishing to try his hand at the interpretation of these results may have the data in usable form from these charts.

The traverse consists of some 470 gravity and magnetic stations with an average spacing of approximately 7 miles. Gravity measurements at each station were made with a gravimeter loaned by the Humble Oil and Refining Company. Magnetic measurements were made with Askania Schmidt vertical field balances. Elevation data were from highway elevations where available and supplemented where necessary by determinations made with Paulin Altimeters. Horizontal control for mapping locations and making latitude corrections was obtained largely from topographic maps at scale 1:62,500 where available and from other maps in other areas.

Some fifty stations of the traverse were completely reduced in their usual fashion by the United States Coast & Geodetic Survey. The reduction of these stations gives a measure of the isostatic anomalies along the traverse and from a curve drawn through the stations so reduced it is possible to obtain approximate isostatic values for all of the stations. The values plotted on the various gravity profiles are the Bouguer anomalies calculated in the usual manner and uniformly for a density of 2.67. Terrain corrections were not calculated and, therefore, are available only for those stations for which the complete reductions were made by the U.S.C. & G.S. The terrain corrections on these stations amount, in some cases, to as much as 17 mg. and, therefore, in the mountainous areas the anomalies, as shown, may be in error (values too low) by amounts up to this

magnitude. (The signs of all values in the "Terrain effect" column of Table 4 should be negative instead of some being positive, as might be inferred from the omission of negative signs.) However, for most of the traverse, the terrain corrections are not large enough to seriously detract from the accuracy of the reduced values.

A considerable part of the text of the report is given over to a review of the significance of gravity and magnetic anomalies in general, and to a brief exposition of the principles of calculating depth, size, etc., for assumed simple geometric forms and from the "half-width" and magnitude of the anomalies themselves. These principles are made use of extensively in later detailed discussions of the various anomalies shown by the traverse. This seems a useful endeavor in that it may bring some of the possibilities of quantitative estimates in connection with the interpretation of gravity and magnetic maps to the attention of geologists who are not otherwise familiar with them, but many geophysicists will consider the applications as somewhat naive and over-simplified.

A quite clear discussion is given of the significance of the Bouguer anomaly curve and its relation to elevation and to the isostatic correction. This discussion should be a material help in explaining these relations to many geologists who seem to find them rather confusing and difficult to understand.

The latter pages of the report are given to a discussion and interpretation of many of the specific anomalies which are shown by the seven detailed profile sheets and a comparison of these anomalies with surface geologic evidences of structure. There are some cases, notably the Uncompaghree Uplift of Utah and Colorado, which are clearly related to gravity anomalies of a reasonable magnitude. There are other cases, such as the Nemaha Ridge in Kansas, where a very pronounced and well-known basement uplift does not have a recognizable gravity anomaly and only a very slight magnetic anomaly. There are still other cases where very pronounced anomalies exist, shown by either gravity or magnetic evidence, or both, but which can not be correlated with any known geologic structure. These quite naturally are referred to probable density contrasts within the basement, which are out of sight and knowledge of geologists, but which may reasonably be inferred to exist. Frequent use is made of calculations of depth and size of gravity or magnetic disturbances, based usually on an assumed simple cylindrical form, to establish orders of magnitude of size which may be compared with such geological factors as are known. On the whole, these comparisons appear reasonable but may be objected to by some geologists because of the over-simplifications involved in using such a simple, geometrical form as the basis for analysis.

The various interpretations of specific features are necessarily highly speculative in many cases and it would be surprising if other geologists would not have different ideas as to the significance of the geophysical features and, therefore, would disagree with some statements which are made rather categorically. However, the reviewer feels that Woollard is to be commended for attempting to put a quantitative limit on his speculations, even if they are over-simplified, as this has saved him from errors frequently made by geologists considering possible causes of geophysical anomalies, who suggest geological situations which may be off by an order of magnitude or two, because they do not appreciate the size of geophysical anomaly which may be reasonably produced by a given size of geologic disturbance. On the other hand, some of Woollard's interpretations may be grossly in error because they are based on a single traverse of data which may not give a typical picture of some of the features which appear prominent on the particular profile traversed. The interpretation necessarily infers that the features

indicated by the profile extend with similar form for some distance to the north and south, which may not be the fact. For instance, it is known that in other parts of Kansas more detailed surveys show a fairly definite but quite local gravity anomaly associated with the Nemaha Ridge.

In spite of its limitations and the objections which might be raised to some of the interpretations, the results given by Woollard are a tremendous addition to the geophysical knowledge of the North American continent. In years to come, other traverses with more closely spaced stations or more completely reduced values may be carried out, but this will always remain as the first continuous geophysical traverse across the United States. To those who may not be willing to accept the interpretation made, the data are now available so that they should be able to work out ideas of their own to their heart's content. Prof. Woollard and his associates have thus made available enough material to keep speculative geologists and geophysicists busy for a long time to come.

L. L. NETTLETON
Pittsburgh, Pennsylvania

Geologic Correlation of Areal Gravitational and Magnetic Studies in New Jersey and Vicinity. George P. Woollard. Bulletin of the Geological Society of America, Vol. 54, Pages 791 to 818, June 1, 1943.

This paper gives the geophysical results and interpretation for a rather close net of gravity and magnetic stations in the southern two-thirds of New Jersey and eastern Pennsylvania. Over most of the New Jersey parts, the stations are at intervals of about 3½ miles on profiles roughly ten miles apart, running approximately NW-SE, or across the strike of the Appalachian trends. This work is supplemented by a zone of much closer control extending in a band about four miles wide reaching from Barnegat Bay on the coast, northwestward through Princeton and Flemington to the Delaware River at Phillipsburg, New Jersey. In this eighty mile long band, gravity and magnetic stations were established at intervals of about 0.3 miles on profiles about a mile apart. In all, 2,098 gravity and magnetic stations were established of which about half are in the detailed strip. A gravity map has been made in which these stations are supplemented by other gravity stations in eastern Pennsylvania, northeastern Maryland, southern New England and Long Island, including stations made by the U. S. Coast & Geodetic Survey, those made as part of Woollard's transcontinental traverse and some from the Gulf Research & Development Company traverse across Pennsylvania.

The geologic interpretation of the results is divided into two parts. The first considers the large scale or regional features, most of which have been discussed and even given names in previous papers on the gravity work in this area by Longwell, Thom, Nettleton and Elkins. Some of the smaller features can be correlated with known geologic features. The discussion contains a number of estimates of probable densities of individual parts of the section, and the density contrasts which might be expected, together with a comparison of the magnitude of roughly calculated gravity effects with those observed. On the whole, these comparisons seem rather reasonable, although others might not agree in the details of the magnitude of relatively local anomalies as inferred from the observed values. Some of the larger features of the map can not be definitely correlated with any known geologic features of the area and, therefore, are referred to density contrasts several miles deep and which are, undoubtedly, associated in some way with the tectonics of the Appalachian uplift, but for which only very gen-

eral suggestions are offered. The reviewer considers it unfortunate that Prof. Woollard has not considered the quantitative aspects of mountain building, as first proposed by Gunn[1] and tested with respect to this particular area by Elkins.[2]

The regional aspects of the magnetic results are also considered briefly. It is pointed out that, due to the lack of agreement of their gross features, they must not arise from the same sources as the large gravity features. The magnetic picture is disturbed by very sharp and strong anomalies over some of the igneous instrusions in the Triassic belt which crosses this area. In general, the larger magnetic anomalies seem to have a shallower origin than the large gravity features.

A rather careful analysis is made of the detailed gravity and magnetic data along the band of detailed surveys. This area has had considerable discussion in the past, as it is the same as that of the "Barnegat Bay" traverse on which Ewing[3] shot a series of refraction seismograph profiles to determine the basement depth. The gravitational aspects also have been discussed previously,[4] as a line of relatively closely spaced pendulum stations across this same area was set out by the U. S. Coast and Geodetic Survey. Woollard's data now give a really good magnetic and gravity survey on this band across New Jersey.

Gravity results have been interpreted after the subtraction of a regional. The original data across this strip show a relief of some 97 mg. A smoothed-out regional map has been developed in two successive stages from the original data. The regional includes the larger features of the map and takes out some 90% of the relief, as the residual map shows values ranging from $+7$ to -4 mg. The magnetic map was not modified as the features are so sharp and strong that they are clearly evident from the observed data.

The relation of the magnetic and the residual gravity map to the rather complicated geology of the area is discussed in considerable detail. The area is a good one for a test, as it extends from outcrops of pre-Cambrian gneiss and Ordovician limestone on the west, across the Triassic graben with its numerous diabase dikes and intrusions, to the coastal plain with its overlap of Cretaceous and Tertiary sediments. The interpretation considers the probable density contrast and again includes roughly quantitative calculations of the magnitude of gravity and magnetic effects which might be expected, and compares them with those observed. Some inferences are made with regard to certain features of geology, such as thrusting of the gneiss over the pre-Cambrian limestone, which perhaps adds significant detail to the geological knowledge of the area. As might be expected, the detailed work has shown definite and strong magnetic and gravity anomalies associated with the igneous instrusions within the Triassic trough. Some inferences are made as to the probable form and extent of certain of these masses beyond the limits to which they are known from surface geology.

Some rather strong gravity anomalies in the eastern part of the survey, where it is over the coastal plain, must arise from density contrasts within the basement, which is composed of metamorphic rock. In this area there is no very definite relation between the gravity and magnetic anomalies.

The paper contains the following maps, all of which are printed as folded inserts

[1] Jour. Franklin Inst., Vol. 224, pp. 19–53, 1937.

[2] GEOPHYSICS, Vol. 7, No. 1, January 1942, pp. 45–60.

[3] Bull. Geol. Soc. of Am., Vol. 50, pp. 257–296, 1939.

[4] Woollard, Am. Geophysics Union, Trans. of 21st Meeting (1940) pp. 301–309. Nettleton, GEOPHYSICS, Vol. 4, No. 3 (July 1939) pp. 176–183.

and are of sufficient size and clarity so that all of the data are presented in very useful form. Plate 1—Location of Control Stations for Regional Gravity Survey. Plate 2—Regional Isoanomaly Gravity and Magnetic Map. Plate 3—Regional Geologic Map. Plate 4—Gravity Map of Area Surveyed in Detail (showing development of the regional) and Plate 5—Comparison of Gravimetric, Magnetic and Geologic Data over Area Surveyed in Detail. To the reviewer it seems unfortunate that a cross-section over the area surveyed in detail was not made. Such a section, showing the geology as inferred from the surface exposures and from the refraction seismograph work of Ewing, together with the magnetic and residual gravity anomaly curves, probably would make many of the details of the anomaly curves and their relation to the geology much more evident than they are from the maps.

Prof. Woollard is to be congratulated for having made available a really detailed set of geophysical data over a test area which contains such a variety of geological situations. It should serve to point out the possibilities and limitations of gravity and magnetic surveys for the solution of academic geological problems. It is to be hoped that the advent of the gravimeter and the comparatively cheap gravity surveys which are made available by its use may lead to more attempts at the application of geophysical methods to the solution of non-commercial geological problems.

L. L. NETTLETON
Pittsburgh, Pennsylvania

Gravimetric and Magnetic Maps of the State of Missouri

The State of Missouri has recently published gravimetric and magnetic maps of the entire state.

The magnetic map is based on stations at intervals of 2 miles over the central and southern part of the state and at intervals of 1 mile over the northern part and the eastern and western edges of the state. The contour interval is 100γ. These contours only (without station locations or values) are overprinted in red on the standard base map of the State at scale of 1:500,000. The magnetic map is a continuation of a magnetic map of the northwestern part of the state included in "The Geology of Northwestern Missouri," Missouri Geological Survey and Water Resources, Vol. 25, Second Series, 1938.

The gravimetric map is based on gravimeter stations at intervals of approximately 5 miles along the main highways. Station locations and contours of Bouguer Anomaly at "Interval of 50 gravity units" are shown, also overprinted in red on the standard base map at scale 1:500,000. (The "Unit" referred to here is 10^{-4} c.g.s. units, so the contour interval is 5 mg.) Gravity values at the individual stations are not indicated on the map and the basis of reduction (i.e., the density used) is not stated.

The maps are available at a cost of $.50 each from the Missouri Geological Survey, Rolla, Missouri.

L. L. NETTLETON
Pittsburgh, Pennsylvania

PATENTS*

ELECTRICAL PROSPECTING

U.S. No. 2,319,764. S. J. G. Pirson. Iss. 5/18/43. App. 9/10/38. Assign. One-half to Shelly Krasnow.

Method and Apparatus for Geoelectrical Exploration. An electrical transient method of prospecting in which a condenser discharge is used, the time of discharge being less than the time required for a reflected surge to return to the surface.

GEOCHEMICAL PROSPECTING

U.S. No. 2,319,734. L. Horvitz. Iss. 5/18/43. App. 11/4/39. Assign. E. E. Rosaire.

Geochemical Prospecting. A method of correcting soil analysis values for absorptive power of the sample by measuring the amount of clay and sand in sample and dividing the hydrocarbon content by the ratio of clay to sand determined.

U.S. No. 2,320,577. T. H. Dunn. Iss. 6/1/43. App. 2/9/40. Assign. Stanolind Oil and Gas Co.

Geochemical Prospecting. A method of soil analysis prospecting in which shallow soil samples are extracted with a volatile hydrocarbon, decanted, and the solvent evaporated and the soil waxes weighed.

U.S. No. 2,320,681. H. H. Thompson. Iss. 6/1/43. App. 5/21/40. Assign. Stanolind Oil and Gas Co.

Method of Analysing Earth Formations. A method of geochemical well logging in which samples are extracted with a light and also a heavy solvent and the concentration of hydrocarbons in each determined by measuring the density change either directly or or by hydrostatic pressure required to restore the density of the pure solvent.

U.S. No. 2,321,293. G. L. Hassler. Iss. 6/8/43. App. 5/2/39. Assign. Shell Development Co.

Apparatus for Measuring Pressures in Containers. An apparatus for accurately measuring gas pressure changes in bottles containing soil samples and natural gas, the pressure changes being due to decomposition of the gas by hydrocarbon consuming bacteria present in the soil.

GRAVIMETRIC PROSPECTING

U.S. No. 2,316,915. O. H. Truman. Iss. 4/20/43. App. 10/12/39.

Apparatus for Amplifying and Measuring Small Displacements. An indicating device for a gravimeter in which the mass is one plate of a condenser connected in a resonant bridge circuit and supplied with an a-c frequency close to resonance, unbalance of the bridge being detected by a temperature change in the two resistance arms of the bridge, and the indicated displacement being normalized by electrostatic forces from known d-c applied to the condenser plates.

* Abstracts by O. F. Ritzmann, Gulf Research & Development Co.

U.S. No. 2,318,665. F. G. Boucher. Iss. 5/11/43. App. 2/7/41. Assign. Standard Oil Development Co.

Measuring Device. A spring system for a horizontal torsion type gravity meter in which an adjustable auxiliary spring is fastened to a turn of the main spring at right angles and close to the anchor so as to produce a small rotating effect.

U.S. No. 2,319,940, W. A. Marrison. Iss. 5/25/43. App. 9/12/39. Assign. Bell Telephone Laboratories.

Gravitational Force Measuring Apparatus. A gravity meter consisting of a conical pendulum driven by a crystal clock and measuring the variation in capacity of the rotating bob against a fixed electrode by a beat frequency method.

U.S. No. 2,322,615. F.G. Boucher. Iss. 6/22/43. App. 9/8/41. Assign. Standard Oil Development Co.

Leveling Device. A gravity meter sub-base having an upper spherical surface on which three movable and adjustable cups support the instrument.

U.S. No. 2,322,681. H. M. Zenor. Iss. 6/22/43. App. 7/29/38. Assign. Standard Oil Development Co.

Condenser Gravity Meter. A suspended plate condenser type gravity meter having an oscillating circuit into which either the gravity meter condenser or a standard condenser may be connected, and measuring the frequency difference by observing the adjustment required to maintain zero beat with another standard oscillator.

SEISMOGRAPH PROSPECTING

U.S. No. 2,316,354. B. E. Moritz, Jr. Iss. 4/13/43. App. 1/18/40. Assign. Stanolind Oil and Gas Co.

Gain Control. A modified expander for seismograph amplifiers, the expansion being initiated by a time delay relay and the rate of expansion being controlled by the amplitude of the signal.

U.S. No. 2,316,616. F. K. Powell. Iss. 4/13/43. App. 2/11/42. Assign. General Electric Co.

Vibration Responsive Device. A horizontal component permanent magnet suspended coil type dynamic vibrometer having two air gaps in series.

U.S. No. 2,317,334. E. J. Shimek. Iss. 4/20/43. App. 2/21/40. Assign. Socony-Vacuum Oil Co., Inc.

Master Control for Electric Seismographs. A control for seismograph amplifiers in which the shot moment, up-hole impulse, and first arrivals are all recorded on a regular trace and in which amplifier sensitivity is cut down by a delayed action shot moment relay and subsequently expanded as a function of time.

U.S. No. 2,318,624. O. S. Petty and J. O. Parr, Jr. Iss. 5/11/43. App. 8/19/39. Assign. Olive S. Petty.

Automatic Volume Control for Recorder Amplifiers. A seismograph amplifier circuit having A.V.C. on the first two stages through automatic control of grid bias and also having a limiter on the output stage.

U.S. No. 2,318,795. L. J. Peters. Iss. 5/11/43. App. 2/18/37. Assign. Gulf Research & Development Co.

Seismograph Amplifier System. A seismograph amplifier in which the amplification is controlled so as to decrease with increasing signal energy by supplying rectified signal energy to decrease the impedance of a tube shunting one stage of the amplifier.

U.S. No. 2,319,626. L. C. Paslay. Iss. 5/18/43. App. 8/19/37. Assign. National Geophysical Co.

Signal Controlled Amplifier. A seismograph amplifier having an expander tripped by the first arrivals on the first stage and an A.V.C. on a later stage and a limiter on the output.

U.S. No. 2,320,248. E. J. Shimek. Iss. 5/25/43. App. 1/7/42. Assign. Socony-Vacuum Oil Co., Inc.

Method for Seismic Surveying. A method of seismograph shooting in which a number of shots at the same shot point are fired at a definite rate and the receiving equipment is tuned to the predominating frequency.

U.S. No. 2,321,341. B. B. Weatherby and W. T. Born. Iss. 6/8/43. App. 5/26/33. Assign. Geophysical Research Corp.

Seismic Surveying. An expander for a seismograph amplifier in which the first tube grid bias is controlled by a condenser discharge initiated either by the shot moment or a detector impulse.

U.S. No. 2,321,450. L. F. Athy and E. V. McCollum. Iss. 6/8/43. App. 12/14/38. Assign. Continental Oil Co.

Seismic Surveying. A system of continuous reflection profiling in which the line of shot holes is parallel to but displaced from the line of detector stations, the shots and spreads being so laid out that succeeding records will have one trace with the same reflection time and identical reflection points.

WELL LOGGING AND SURVEYING

U.S. No. 2,315, 629. F. L. LeBus. Iss. 4/6/43. App. 7/30/41.

Wall Core Scraper. A device which is lowered on the drill stem and is operated by fluid pressure and which scrapes off side wall samples upon rotation of the drill stem.

U.S. No. 2,315,840. W. J. Crites. Iss. 4/6/43. App. 7/11/38 and 6/8/40. Assign. Phillips Petroleum Co.

Borehole Thermometer. A thermometer consisting of a series of expansion fluid containers shaped like a collapsed sphere with the collapsed surfaces close together.

U.S. No. 2,316,024. B. W. Sewell. Iss. 4/6/43. App. 8/16/40. Assign. Standard Oil Development Co.

Method and Means for Taking Cores. A coring took having above the core barrel a chamber into which gas and oil may separate when pressure is released on bringing the core to the surface.

U.S. No. 2,316,216, A. M. Bandy. Iss. 4/13/43. App. 11/16/40.

Apparatus for Taking Samples of Fluid from Wells. A bottom hole sampler which may be run into the well as a go-devil and which has a pilot to penetrate the formation and withdraw an uncontaminated sample.

U.S. No. 2,316,329. D. G. C. Hare. Iss. 4/13/43. App. 6/18/40. Assign. Texaco Development Corp.

Subsurface Prospecting. A method of increasing the efficacy of neutron well logging by mixing with the neutron source a material in which it will induce nuclear fission.

U.S. No. 2,316,361. R. G. Piety. Iss. 4/13/43. App. 3/17/41. Assign. Phillips Petroleum Co.

Method and Apparatus for Surveying Wells. A gamma ray method of determining direction of dip of formations encountered in a well by rotating a Geiger counter having a collimating shield and observing the variation in gamma ray intensity with azimuth.

U.S. No. 2,316,576. R. E. Fearon. Iss. 4/13/43. App. 8/14/40. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. A bridge circuit for the ionization chamber of a radiation logging apparatus whereby changes in battery voltage are compensated.

U.S. No. 2,316,942. H. G. Doll. Iss. 4/20/43. App. 12/27/37, 5/6/41 and 1/7/37. Assign. Schlumberger Well Surveying Corp.

Apparatus for Measuring Temperatures in Boreholes. A bridge circuit for a resistance thermometer in which one lead of either the current supply or the indicator is carried by a ground return.

U.S. No. 2,317,039. G. H. Ennis. Iss. 4/20/43. App. 9/25/39. Assign. One-half to Robert V. Funk.

Method and Apparatus for Determining Water Leakages into Wells. Testing for entry of water into a well by means of an apparatus which when actuated distributes a primary cell electrolyte into the section to be tested, and thereafter measuring the emf developed between two electrodes on the apparatus.

U.S. No. 2,317,259. H. G. Doll. Iss. 4/20/43. App. 2/15/38. Assign. Schlumberger Well Surveying Corp.

Device for Determining the Strata Traversed by Drill Holes. A method of electric well logging in which a-c resistivity measurements with two different electrode spacings and also the spontaneous potential are all measured simultaneously.

U.S. No. 2,317,304. C. Schlumberger. Iss. 4/20/43. App. 5/11/35 and 4/5/35. Assign. Schlumberger Well Surveying Corp.

Apparatus for the Electrical Surveying of Boreholes. A three-electrode single wire electrical well logging apparatus in which a current source connected to two electrodes is lowered into the hole and the third electrode is connected via a single conductor cable to a meter and an electrode at the surface.

U.S. No. 2,317,386. G. L. Kothny. Iss. 4/27/43. App. 3/14/42. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instrument. An electrolytically recording plumb bob type inclinometer in which the recording current is held on for only a short time by a relay operated from a battery having a heavy current drain which therefore runs down in a predetermined time.

U.S. No. 2,317,632. L. C. Miller. Iss. 4/27/43. App. 7/20/39. Assign. Eastman Oil Well Survey Corp.

Means for Surveying Well Bores. A single wire surface indicating well surveying device having an inner housing photoelectrically oriented to a compass north and a pendulum hanging in gimbals connected to a contact scanning mechanism which transmits indications of the inclination parameters over the suspending cable at different frequencies.

U.S. No. 2,318,612. G. L. Kothny. Iss. 5/11/43. App. 6/29/40. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Device. A timing device for a single shot well survying instrument in which a conducting liquid flowing through a metering orifice from one tank to another makes an electric circuit at the proper time and breaks it again.

U.S. No. 2,320,643. J. Neufeld. Iss. 6/1/43. App. 5/14/41. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. A method of radioactive well logging in which gun perforator projectiles containing radioactive material is fired into the formations and subsequently one or more radioactive logs run to determine depth of penetration and porosity.

U.S. No. 2,320,863. W. G. Green. Iss. 6/1/43. App. 6/21/40. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. A device for locating well bottom which consists of a magnet on a vertical slide beneath the surveying instrument so that when the magnet is pushed up against the instrument it attracts an armature inside closing a switch to transmit a signal to the surface.

U.S. No. 2,320,890. W. L. Russel Iss. 6/1/43. App. 8/2/41. Assign. Well Surveys, Inc.

Method of Geophysical Prospecting. A method of accurately determining formation depths by placing radioactive material on the casing at preselected locations and running a radioactivity log.

U.S. No. 2,320,892. S. A. Scherbatskoy and R. E. Fearon. Iss. 6/1/43. App. 1/31/42. Assign. Well Surveys, Inc.

Method of Geophysical Prospecting. A method of locating cement behind casing by adding to only alternate layers of cement a radioactive material and subsequently running a radioactivity log.

U.S. No. 2,321,295. L. G. Howell. Iss. 6/8/43. App. 6/23/41. Assign. Standard Oil Development Co.

Apparatus for Logging Boreholes. A radioactivity logging apparatus operating on a

single conductor cable, d-c being supplied to the instrument and stepped up to high voltage for the counter by an oscillator, and the counter pulses recorded as a-c over the supply wire.

U.S. No. 2,321,474. G. F. Fermier. Iss. 6/8/43. App. 1/8/40. Assign. Reed Roller Bit Co.

Core Orienting Device. A multi-pointed tool with which a core can be marked at a known orientation before cutting.

U.S. No. 2,322,238. G. L. Kothny and G. A. Smith. Iss. 6/22/43. App. 6/29/40. Assign. Sperry-Sun Well Surveying Co.

Time Delay Relay Control. A timing arrangement for a single shot well surveying instrument employing an electrolyte flowing through a metering orifice to make and break a circuit at the proper time, electrolysis being overcome by using a relay to shunt the electrolyte and operate the lamps, the relay being released by a thermoelement.

U.S. No. 2,322,478. S. A. Scherbatskoy. Iss. 6/22/43. App. 5/28/40. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. An electrical drilling rate recorder in which as drilling progresses electrical impulses advance a multicontact step switch connected to a series of resistors.

U.S. No. 2,322,634. L. G. Howell and L. W. Blau. Iss. 6/22/43. App. 6/23/41. Assign. Standard Oil Development Co.

Method and Apparatus for Logging Boreholes. A radioactivity logging apparatus having one or more detectors with radial slits and separate recorders to that any asymmetry of activity may be detected for determining dip of formations or non-uniform distribution of cement.

MISCELLANEOUS

U.S. No. 2,315,496. A Boynton. Iss. 4/6/43. App. 11/28/38.

Perforator for Wells. A method and apparatus for perforating casing by pumping abrasive fluid down a pipe and directing the abrasive stream outward against the casing from radial holes in the pipe.

U.S. No. 2,315,590. C. D. Cantrell. Iss. 4/6/43. App. 7/14/41. Assign. Phillips Petroleum Co.

Coring Apparatus. A core barrel for use on the end of the drill pipe and which traps its core by a mechanism tripped by a go-devil.

U.S. 2,315,819. C. H. Schlesman. Iss. 4/6/43. App. 9/14/40. Assign. Socony-Vacuum Oil Co., Inc.

Method of Exploring Operating Structures. A method of inspecting the interior of refinery or pipe line equipment by simultaneously moving a source of penetrating radiation and a radiation detector on opposite sides of or in parallel parts of the equipment and measuring the strength of radiation transmitted.

U.S. No. 2,316,203. E. E. Simmons, Jr. Iss. 4/13/43. App. 2/23/40 and 7/1/42.

Strain Responsive Device. A strain gauge consisting of a fine wire cemented to one side of a cantilever spring.

U.S. No. 2,316,239. D. G. C. Hare. Iss. 4/13/43. App. 8/20/41. Assign. The Texas Co.

Method and Apparatus for Determining Density of Fluids. A method of determining the density of inaccessible fluids in pipes or reaction vessels consisting of applying a source of penetrating radiation and measuring the absorption and scattering produced by the liquid.

U.S. No. 2,316,494. R. Tipton. Iss. 4/13/43. App. 5/12/41. Assign. W. C. Dillon & Co., Inc.

Oil Well Pump Controller. An automatic device for shutting down a pumping rig as soon as oil is no longer produced, waiting a predetermined interval of time and then resuming pumping.

U.S. No. 2,316,728. R. R. Thompson and W. D. Mounce. Iss. 4/13/43. App. 10/17/40. Assign. Standard Standard Oil Development Co.

Gun Perforator. A firing chamber and loading method for a gun perforator, the powder chamber of which is arranged so that when the bullet is loaded into the firing position it compresses a finely divided explosive powder into the powder chamber.

U.S. No. 2,317,008. R. R. Chappell and R. B. Colt. Iss. 4/20/43. App. 8/6/41. Assign. Bendix Aviation Corp.

Accelerometer. A mechanically indicating accelerometer in which the steady mass is supported between two metallic bellows and damped by the flow of liquid from one bellows to the other.

U.S. No. 2,317,199. H. M. Kirschbaum. Iss. 4/20/43. App. 4/21/41.

Electromagnetic Sound Recorder. A magnetic tape recorder which is magnetically biased and which has no air gap.

U.S. No. 2,317,202. W. Kohlhagen. Iss. 4/20/43. App. 2/21/40. Assign. Waterbury Clock Co.

Apparatus for Timing Impulses. A device for comparing the spacing of impulses of a timepiece with a standard frequency by means of two thyratrons, one of which fires at the first impulse and the other acts as a snuffer at the second impulse.

U.S. No. 2,317,718–721. W. C. Barnes and H. W. Keevil. Iss. 4/27/43. App. 6/6/38, 6/8/35, 4/17/40, 5/11/40.

Method and Apparatus for Detecting Flaws in Magnetizable Bodies. Methods and apparatus and improvements in detecting flaws in elongated steel shapes such as rails by subjecting them to various types of strong magnetic fields and measuring the residual magnetism shortly after removal of the magnetizing device.

U.S. No. 2,318,062. T. R. Dames. Iss. 5/4/43. App. 11/29/40. Assign. Dames & Moore.

Soil Sampler. A soil sampler or core cutter in which the inside surface has no obstructions and having a core catcher which is flush with the inside surface when cutting.

U.S. No. 2,318,102. A. C. Ruge. Iss. 5/4/43. App. 9/15/41.

Rosette Type Strain Gauge. A resistance type strain gauge element consisting of a number of fine wires embedded in a thin membrane which can be cemented to the member under test.

U.S. No. 2,318,248. J. P. Minton. Iss. 5/4/43. App. 2/21/40. Assign. Socony-Vacuum Oil Co., Inc.

Phase Meter. A method of testing amplifiers for phase shift by simultaneously applying the same input signal to both and connecting their loaded outputs so that the amplifiers feed a common high resistance whose voltage drop may be measured and phase angle computed.

U.S. No. 2,318,601. F. C. Doble. Iss. 5/11/43. App. 6/22/39. Assign. Doble Engineering Co.

Electrical Means for Indicating Temperature Conditions. A theromometric device for indicating average temperature condition which consists of two insulated wires and obtaining the temperature from a measurement of the insulation resistance between them.

U.S. No. 2,318,689. L. R. Hodell and J. J. Heigl. Iss. 5/11/43. App. 12/27/41. Assign. Standard Oil Development Co.

Tracing Gas Through Underground Formations. Tracing the underground course of gas in repressuring operations by mixing with the injected gas carbon monoxide, hydrogen, or nitric oxide and analysing the produced gas for presence of these tracing agents.

U.S. No. 2,318,720. B. W. Sewell. Iss. 5/11/43. App. 11/12/40. Assign. Standard Oil Development Co.

Magnetic Permeability Indicator. A pocket device for indicating the critical point of cooling steel such as in a weld, consisting of a permanent magnet with pole piece and an indicating armature which shifts position as the flux shifts from the pole piece to the cooling steel as it becomes magnetic.

U.S. No. 2,320,290. E. M. McNatt. Iss. 5/22/43. App. 8/8/41. Assign. Standard Oil Development Co.

Integrating Gradiometer. An apparatus for making elevation surveys consisting of a light source emitting impulses proportional to the distance travelled by a vehicle and transmitting to a photocell a fraction of these impulses proportional to the sine of the angle of inclination of the vehicle through a pendulum and shutter device, and counting the total number of light impulses received by the photocell.

U.S. No. 2,320,492. C. P. Walker. Iss. 6/1/43. App. 8/11/38.

Method of Determining Fluid Pressure and Production Capacity of Oil Wells. Measuring the production rate of a pumping well as a function of casing head pressure and from the graph determine the pump inlet pressure, productivity index and production capacity of the well.

U.S. No. 2,321,680. J. V. Houston. Iss. 6/15/43. App. 3/10/42.

Post Hole Digger. An earth auger driven from the power take-off of a tractor and so arranged that holes may be drilled at any angle and in any position with respect to the tractor location.

U.S. No. 2,322,064. B. W. Sewell. Iss. 6/15/43. App. 12/22/41. Assign. Standard Oil Development Co.

Coring Device. A pressure core barrel which cuts the core and by a go-devil released valve and piston operated by mud pressure draws the core into a sealed chamber.

U.S. No. 2,322,231. W. L. Fischer. Iss. 6/22/43. App. 8/14/40.

Optical Amplifier. A moving mirror displacement indicator whose mirror is made up of a number of small facets or a curved surface so that as the incident light falls on a different portion of the mirror the deflection of the reflected beam is increased.

U.S. No. 2,322,263. E. E. Turner, Jr. Iss. 6/22/43. App. 10/2/37 and 12/21/40. Assign. Submarine Signal Co.

Electromagnetic Recording Mechanism. An ink recording chronograph in which an actuating element consisting of a short circuited turn on a transformer core impresses the paper against a rotating helical inking blade.

U.S. No. 2,322,264. E. E. Turner, Jr. Iss. 6/22/43. App. 11/22/40 and 7/25/41. Assign. Submarine Signal Co.

Apparatus for Echo Distance Measuring. A tuned amplifier for echo sounding in which the sensitivity is controlled by varying the amount of inverse feed-back so that the tuning is broad for shallow soundings requiring low sensitivity and sharp for deep soundings requiring high sensitivity.

U.S. No. 2,322,319. A. C. Ruge. Iss. 6/22/43. App. 9/16/39 and 7/15/42.

Strain Responsive Device. A wire filament strip type strain gauge which is temperature compensated by having a second filament laid across the strip and connecting the filaments in two arms of a Wheatstone bridge circuit.

U.S. No. 2,322,343. A. H. Brandon. Iss. 6/22/43. App. 10/14/40. Assign. Dia-Loy Co.

Tubing Wear Detector. A caliper device for locating worn places in well tubing, the caliper fingers making electric contacts which control an electric clapper in the instrument, the vibration being picked up by electroacoustic means at the surface.

U.S. No. 2,322,484. R. W. Stuart. Iss. 6/22/43. App. 9/20/40. Assign. Stanolind Oil and Gas Co.

Method for Removing Mud Sheaths. A method of completing a well by washing with a relatively concentrated detergent solution of either phosphate, acid phosphate, disodium pyrophosphate or disodium phosphate.

U.S. No. 2,322,621. F. K. Farrow. Iss. 6/22/43. App. 10/2/41. Assign. Philco Radio and Television Corp.

Electroacoustic Transducer. A condenser type phonograph pick-up or microphone in which the condenser consists of two metallic strips separated by a dielectric, the unit being pretwisted and actuated torsionally.

U.S. No. 2,322,816. H. T. Boeker. Iss. 6/29/43. App. 5/25/40. Assign. General Electric X-Ray Corp.

Galvanometer. A moving mirror galvanometer consisting of a polarized type magnetic reproducing element connected to a pivoted arm supporting a mirror.

U.S. No. 2,322,861. G. P. Luckey. Iss. 6/29/43. App. 11/24/37. Assign. Hamilton Watch Co.

Constant Speed Body. A constant speed rotating element driven at approximately correct speed by a motor through viscous coupling and periodically given a correcting electromagnetic impulse from a timepiece.

U.S. No. 2,323,128. D. G. C. Hare. Iss. 6/29/43. App. 9/10/41. Assign. The Texas Co.

Method and Apparatus for Determining Liquid Level. A method of locating an interface inside a closed container by applying a source of penetrating radiation to the outside and measuring the radiation which is transmitted through to the opposite side of the container or measuring the ratio of transmitted to scattered radiation.

U.S. No. 2,323,211. F. J. Faltico. Iss. 6/29/43. App. 5/23/41.

Method and Apparatus for Automatic Gain Control. An A.V.C. system for audio amplifiers in which the screen potential of one or more tubes is derived from the plate connection of a succeeding tube.

PUBLICATIONS RECEIVED

(The publications listed below were received since issuance of GEOPHYSICS for July, 1943, and are available for loan to the membership. Articles cited are those considered of particular interest to geophysicists.)

Aerial Photographs: Their Use and Interpretation, by A. J. Eardley. Harper & Brothers (New York, 1942).

American Journal of Science, Vol. 241, Nos. 5, 7, and 8 (May, July, and August, 1943, New Haven).

Bulletin of the American Association of Petroleum Geologists, Vol. 27, Nos. 2–8 (February–August, 1943, Tulsa).

Economic Geology, Vol. XXXVIII, Nos. 4, 5 (June–July, August, 1943, Lancaster).

Independent Petroleum Association of America Monthly, The, Vol. XIV, Nos. 2, 3, 4 (June, July, August, 1943, Tulsa).

Journal of Applied Physics, Vol. 14, Nos. 5, 6, 7 (May, June, July, 1943, Lancaster).

Journal of the Institute of Petroleum, Vol. 29, Nos. 233, 234, 235 (May, June, July, 1943, London).

Petroleum, Vol. VI, Nos. 5, 6 (May, June, 1943, London).

Physics Abstracts, Vol. 46, No. 546 (June, 1943, London).

Proceedings of the Cambridge Philosophical Society, Vol. 39, Parts 1, 2 (March, June, 1943, Cambridge).

Review of Scientific Instruments, The, Vol. 14, Nos. 5, 6, 7 (May, June, July, 1943, Lancaster).

Revista de Ciencias, Vol. XLIV, No. 442 (December, 1942), Vol. XLV, No. 443 (March, 1943), (Lima).

World Petroleum, Vol. 14, Nos. 6, 7, 8 (June–July, 1943, New York).

CONTRIBUTORS

JOHN J. RUPNIK received the B.S. degree in geological engineering, geophysical option, from the Colorado School of Mines in 1933. From this date until 1939 he was employed by the Texas Company as assistant recorder, computer, and party chief. In 1939 he left the field to work towards a Ph.D. in geophysics, and received the M.S. degree in geology in 1941. Mr. Rupnik is currently employed by the United Geophysical Company as a party chief.

J. BRIAN EBY attended Johns Hopkins University, where he received the B.A. degree in 1918 and the Ph.D. degree in 1922, with geology as major subject. In the employ of the United States Geological Survey from 1919 to 1925, he was stationed variously in Washington, D. C., and in the Appalachian and Rocky Mountain states. He entered the employ of Shell Petroleum Corporation in 1925, resigning in 1931 to set up as an independent consulting geologist in Houston. During recent months Dr. Eby has been serving as a lecturer and instructor in night classes for war training in aerial photogrammetry.

PAUL F. HAWLEY received the degree of B.S. in E.E. from the University of Arizona in 1932, and the M.S. in E.E. and Ph.D. degrees from the California Institute of Technology, the latter in 1936. Dr. Hawley became associated with the joint geophysical laboratory of the Stanolind Oil and Gas Company and the Western Geophysical Company in 1935, and in 1940 was transferred to the Stanolind general office as patent advisor. In 1941 he was transferred to the Development and Patent Department of the parent company, Standard Oil Company (Indiana), with headquarters in Chicago. Dr. Hawley is registered to practice before the Patent Office.

ANDREW BROWN received his B.S. degree from the University of Texas in 1934. Employed by the Texas Highway Department 1934 through 1935 on a surveying crew, and later assistant office engineer; 1936 by the Resettlement Administration as Party Chief on land surveys; served as senior computer on seismograph crew with Seismic Explorations, Incorporated, 1936 through 1938. Chief computer and field supervisor for Mott-Smith Corporation since 1939.

H. KLAUS received his E.M. degree from the Royal Mining Academy, a branch of the Institute of Technology of Berlin—Charlottenburg, Germany, in 1925. From that time until 1927, he was engaged in geological and torsion balance work for the North American Exploration Company of Houston, Texas. From 1927 to 1932, he was in charge of torsion balance work for the Gypsy Oil Company of Tulsa, Oklahoma. In 1932, he was transferred to the research laboratory of the Gulf Oil Corporation at Pittsburgh, Pa., where he was engaged in the interpretation of reflection seismograph and gravimetric surveys until 1936. In that year, he organized Klaus Exploration Co., which specializes in gravimetric work, utilizing both the torsion balance and the gravity meter. He is a member of the American Association of Petroleum Geologists, and of the Society of Exploration Geophysicists.

J. A. LEGGE, JR., received his B.S. in Geophysics from the California Institute of Technology in 1937 and his M.S. in Geology from the University of Arizona in 1939, after which he was employed by the Standard Oil Company of California. In 1942 he joined the research department of the United Geophysical Company. His work with United is largely concerned with seismic interpretation.

Mr. Legge is a member of Sigma Xi, Tau Beta Pi, the American Geophysical Union, and the Society of Exploration Geophysicists.

Photographs and biographies of contributors to this issue not appearing above have appeared previously, as follows: JOSEPH L. ADLER, Vol. VII, No. 1, p. 100, (January 1942.); E. V. MCCOLLUM, Vol. VIII, No. 1, p. 72, (January 1943.); S. S. WEST, Vol. VIII, No. 2, p. 187, (April 1943.).

THE SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Kingsland Arnold
William C. Woolley, Paul E. Nash, Henry C. Cortes

Daniel Webster Autrey
H. Hallock Brown, W. W. Newton, J. E. Jett

Vernon Eugene Briard
L. A. Scholl, Jr., George D. Mitchell, Jr., Roy L. Lay

John Carr
D. R. Brown, H. C. Maliphant (Article III-D-1 of the Constitution)

Joe Edwin Connell
Andrew Gilmour, A. I. Innes, J. R. Winnek

William Reaves Dortch, Jr.
T. R. Moorman, H. H. Frost, J. F. Judson

William Alvin Drennan
Curtis H. Johnson, Henry Salvatori, Dean Walling

Ralph Emery Hartline
Joseph A. Sharpe, Daniel Silverman, C. E. Buffum

Harold M. Lang
C. E. Buffum, Vincent Emanuel, A. C. Reid

Kenneth Gale McCann
T. I. Harkins, E. D. Williams, J. O. Hoard

John William Millington
W. G. Smiley, Jr., L. G. Ellis, W. E. Hollingsworth

Reuel Wallace Mossman
A. J. Barthelmes, F. B. Leedy, T. A. Manhart

David Wallace Ratliff
K. E. Burg, Karl Dyk, Garvin L. Taylor

Frederick LeVerne Serviss
(Article III-D-1 of the Society Constitution)

John Raymond Sloat
Louis N. Waterfall, Henry Salvatori, J. A. Gillin

James Archibald Smith
L. K. Morris, C. H. Dix, C. E. Reel

Randolph Smith
T. R. Shugart, W. W. Newton, E. E. Wilson

DeWitt Eugene Taylor
H. R. Thornburgh, Frank Ittner, Phil P. Gaby

Reese Herrick Tucker
August F. Beck, Robert L. Kidd, Arthur E. Dietert
Ray William Walling
Sidon Harris, K. E. Burg, L. H. Wise
Kenneth Ross Weatherburn
D. R. Brown, H. C. Maliphant (Article III-D-1 of the Constitution)

ASSOCIATE

Robert Baum
F. B. Leedy, G. H. Westby, T. A. Manhart
Tun Yin Chang
R. F. Van Cleave, Charles C. Williams, J. H. Pernell
Raymond Francis Cooke
H. B. Peacock, J. W. Thomas, O. T. Lawhorn
Peter Dehlinger
Beno Gutenberg, H. R. Thornburgh, C. H. Dix
Richard H. Fretter
Robert H. Mansfield, J. A. Legge, Jr., C. H. Dix
Edwin Henderson Robinson
K. J. Warren, S. Zimerman, D. H. Gardner

TRANSFER FROM ASSOCIATE TO ACTIVE STATUS

M. M. McCaleb
Elbert F. McMullin
Homer Eugene Roberts
Robert Joseph Urick

PERSONAL ITEMS

DONALD M. DAVIS, formerly a Party Chief for the United Geophysical Company, has accepted a position as Geologist with the Richfield Oil Corporation, 560 Haberfelde Building, Bakersfield, Calif.

JOHN JAY JAKOSKY, Dean of the School of Engineering and Architecture of the University of Kansas for the past several years, has been appointed Director of Industrial Research and Assistant to the President of the University of Southern California. His mailing address is 102 Administration Bldg., U. S. C., University Park, Los Angeles, Calif.

RALPH T. DUFFNER has accepted a commission as Ensign in the U. S. Navy. Mail should be addressed to him at 2801 E. Colfax, Denver, Colo.

D. H. WOODARD, formerly with Gulf, has accepted a position as Gravity Party Chief with the Miller Geophysical Co., 9730 Wilshire Blvd., Beverly Hills, Calif.

PHIL. F. MARTYN has resigned his position as Chief Geologist with the Houston Oil Co. to enter consulting work. His address is 2020 Albans Rd., Houston 5, Tex.

GEORGE C. MCGHEE, who has been serving as Deputy Executive Secretary of the Combined Raw Materials Board, has accepted a commission as Lieutenant (jg) in the U. S. Navy, reporting to Section M, Naval Air Station, Clinton, Okla.

A. I. INNES is now Supervisor for the Geophysical Research Corp., P. O. Box 2040 Tulsa, Okla.

M. L. BENKE, 1st Lt. in the U. S. Army Signal Corps, is now in foreign service. His address in the U. S. is 802 Waverly Ave., San Antonio 1, Tex.

PERTEV I. BEDIZ, who has been serving in the Dept. of Geology at M. I. T., has accepted a position as Chief Computer with the National Geophysical Co. He is currently located at P. O. Box 532, Rosenberg, Tex.

1ST LT. ROY A. HILL, U. S. Army Signal Corps, should be addressed at 430th Sub. Depot (Signal), Allenhurst, N. J.

KENNETH H. WATERS has advised the Society that he has been commissioned 1st Lt. in the British Army. He is stationed at Loggan House, Ballantrae, Ayrshire, Scotland.

H. M. HORTON has moved from Mt. Carmel, Illinois, to 2025 Eye St., Eureka, Calif.

C. C. ZIMMERMAN has left the Texas Co. to accept a position as Manager of the Keystone Exploration Co., 2813 Westheimer Rd., Houston, Tex. Mr. Zimmerman's home address is 4012 Inverness Drive, Houston 6. H. W. MCDONNOLD, formerly Party Chief with the Texas Co., has also joined the new company. Mr. McDonnold's home address is 3829 Gertin St.

E. D. LYNTON, Research Geologist and Engineer with the Standard Oil Co. of California, is now serving with the Office of Economic Warfare on overseas duty. He should be addressed as follows: E. D. Lynton, Civilian, APO 759, NAEB, c/o Postmaster, New York, N. Y. Mr. Lynton plans to return to Whittier at the end of the year.

F. W. OUDT, of the Shell Oil Co., is now located at P. O. Box 1007, Saginaw, Michigan, following transfer from Centralia, Ill.

CAPT. JOHN M. GOLDEN has been transferred from Fort Knox to 216 Armored Eng. Bn., Headquarters Co., Camp Chaffee, Ark.

R. F. ALDREDGE, of the Seismograph Service Corp., is located in Barranquilla, Colombia, doing geophysical work for the Tropical Oil Co.

R. M. Low has left the Independent Exploration Co. to accept a position with the Seismograph Service Corp., 709 Kennedy Bldg., Tulsa, Okla.

ROBERT H. RAY has advised the Society that Lt. Norman P. Teague should be addressed at Hq. 11th Bomber Command, APO 980, Seattle, Wash.

RICHARD D. BUCH, Engineer with Schlumberger, has been transferred from New Iberia, La., to 170 W. Elm St., Coalinga, Calif.

CAPT. G. W. HOSTETLER, Signal Corps, is located at 1403 S. Main St., Goshen, Indiana.

TOM D. MAYES, THOMAS J. BEVAN and W. E. BROGAN, JR., respectively Gravity Supervisor ten years, Chief Gravity Computer seven years, and Party Chief ten years, announce the opening of Mayes-Bevan, Inc. The new firm will specialize in gravity meter surveys, with headquarters at 305 Kennedy Bldg., Tulsa, Okla.

LT. RAY K. CARTER is serving with the U. S. Navy at the Naval Air Station, Terminal Island, Calif.

LT. JAMES A. BALLARD, Communications Officer in the Army Air Corps, is now on overseas duty. His home address is 507 Raton Ave., La Junta, Colo., while the most recent overseas address furnished the Society is 12th A.A.C.S. Region, APO 604, c/o Postmaster, Miami, Fla.

EUGENE WIANCKO, of the United Geophysical Co., is located at Box 1269, Odessa, Texas.

G. STUBBE should be addressed at Box 788, Crystal City, Tex.

LT. IR. J. J. H. JANSEN M., Dutch Air Force, has been transferred to 1018 N. State (I 6), Chicago 10, Ill., from Jackson, Miss.

In the recent reorganization of the Standard Oil Co. of New Jersey Group of Venezuela, G. F. KAUFMANN has advised the Society that he will retain his post as Chief Geophysicist, with operating units combined under the name of the Creole Petroleum Corp., Aptdo. 1329, Caracas, Venezuela, S. A.

SAM ZIMERMAN, Party Chief for the Carter Oil Co., has moved from Hazlehurst, Miss., to Box 951, Torrington, Wyo.

CAPT. LEONARD F. UHRIG has been advanced to the rank of Major. His mailing address is Maint. Bn., 5th A. D., APO 255, Pine Camp, N. Y.

Advancement to the rank of Major was also earned by CAPT. WILLIAM E. STEELE, JR., U. S. Army Signal Corps, Washington, D. C. Major Steele's Washington address is 4119 W NW.

LT. JAMES A. BROOKS, JR., U. S. N. R., is located at the Naval Mine Warfare Test Station, Solomons, Md.

R. B. COIT, formerly with G. S. I. in Dallas, Texas, has become a partner in Coit Brothers, with offices at 1509 Magnolia Bldg., Dallas 1, Tex.

RALPH C. HOLMER has left the Mott-Smith Corp. to accept a position as Physicist at the Charleston Navy Yard, Charleston, S. C.

A. B. MANNING, on military leave from the Magnolia Pet. Co., is serving as 1st Lt. in the U. S. Army.

L. B. TROMBLA, Party Chief with the Superior Oil Co., is located at P. O. Box 289, Red Bluff, Calif.

FIELDING L. MITCHELL has been commissioned Lieutenant (jg) in the U. S. N. R., and is currently located in the Office of the Assistant Industrial Manager, 242 W. 7th St., San Pedro, Calif.

TH. KOULOMZINE should be addressed at P. O. Box 870, Val D'Or, Quebec, Canada.

ALLEN M. RUGG, JR., is now employed by the Anchor Exploration Co. His home address is 3241 W. 22nd Ave., Denver 11, Colo.

CAPT. HARRY R. IMLE, recently located at Fort Sill, Okla., should now be addressed at APO 722, Group A, Seattle, Wash.

HARRY L. THOMSEN, of the Shell Oil Co., Inc., has been transferred from Bakersfield, Calif., to 156 S. Center St., Casper, Wyo.

J. EUGENE STONES, Party Chief with the Superior Oil Co., has been transferred to P. O. Box 247, Seminole, Tex.

O. B. JACKSON and ROBERT L. GEYER, of the Shell Oil Co., Inc., are currently located at Box 106, Bad Axe, Mich.

HERBERT J. FERBER and H. L. RASÉ, JR., of the Western Gulf Oil Co., have been transferred from Fresno to 401 19th St., Bakersfield, Calif.

E. V. MCCOLLUM and CRAIG FERRIS have resigned from the Mott-Smith Corporation, in which Mr. McCollum was chief geophysicist and Mr. Ferris was a party chief. They have formed E. V. McCollum and Company, to engage in gravity and seismic explorations. They may be reached at P. O. Box 2646, Tulsa 1, Oklahoma.

Society members are requested to send in their postal zone numbers promptly in order to aid the Postal Department in its zoning plan. Addition of postal zone numbers will expedite handling of all mail matter, and will assure members that GEOPHYSICS will reach them quickly.

THE HOUSTON GEOLOGICAL SOCIETY held its first regular meeting of the season at the Texas State Hotel at noon on Thursday, September 16. Dr. J. Brian Eby delivered a paper entitled "The Oil and Gas Fields of Jackson County, Texas." A special meeting was held at noon on September 20 at which Dr. J. B. Ruside, Jr., of the U.S.G.S. presented a paper on "Some Features of Sedimentation of the Upper Cretaceous of the Western Interior." Hilliard W. Carey, secretary of the Society, extends an invitation to all geophysicists of Houston to attend these meetings.

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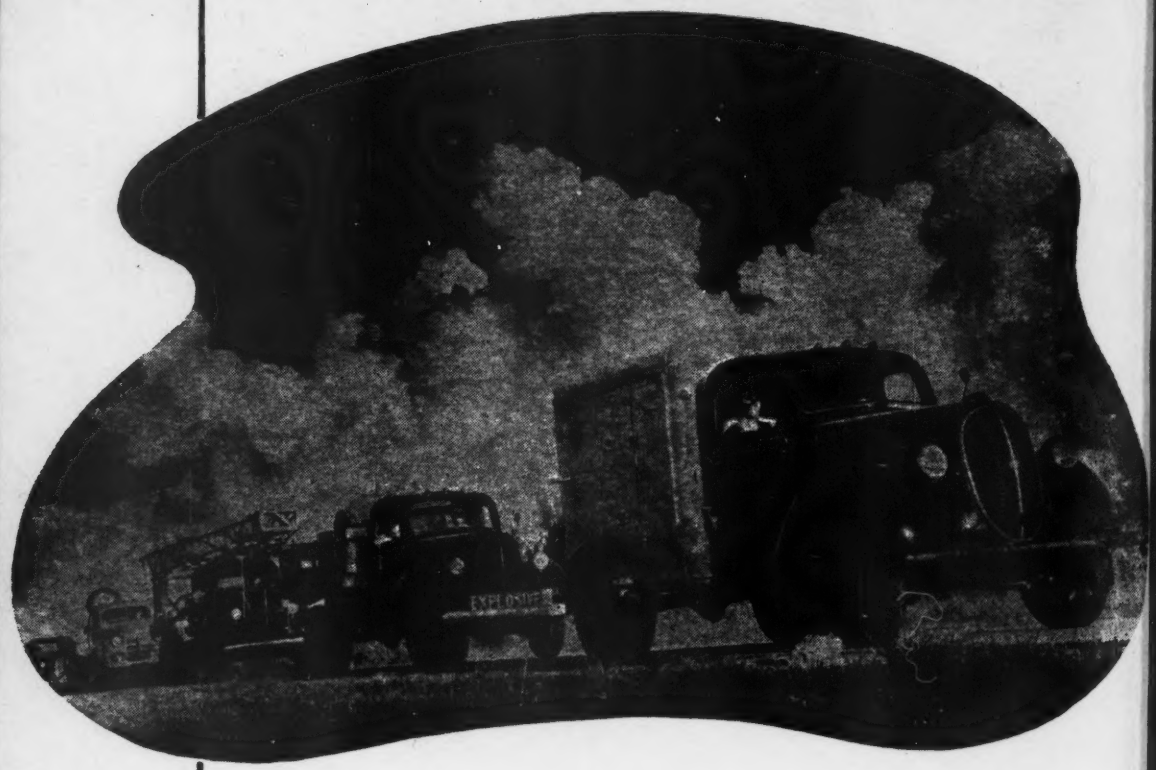

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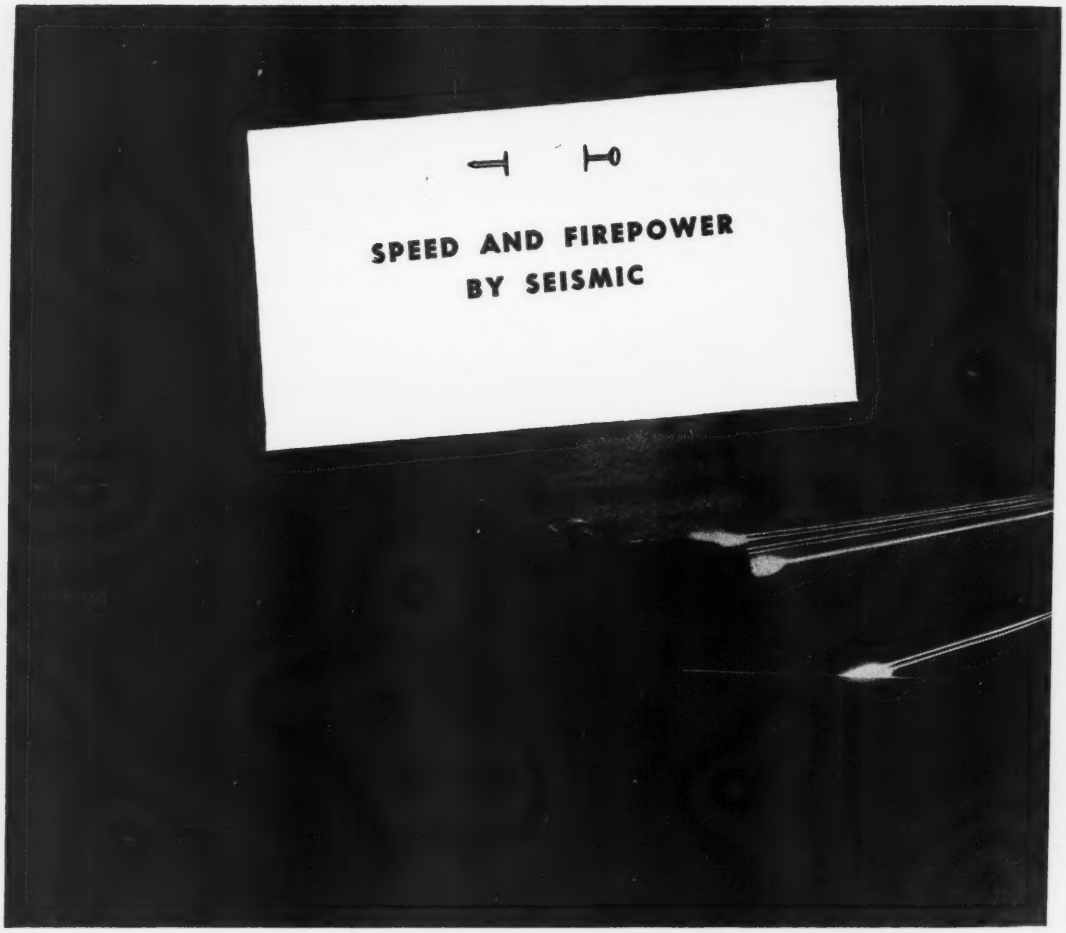

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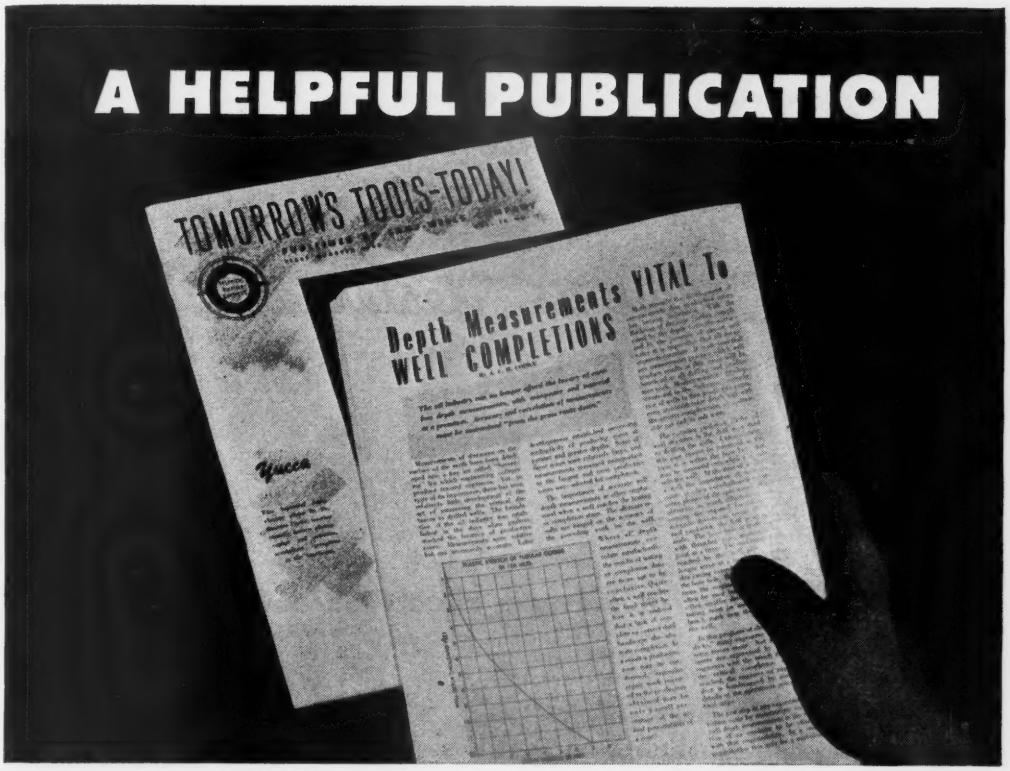

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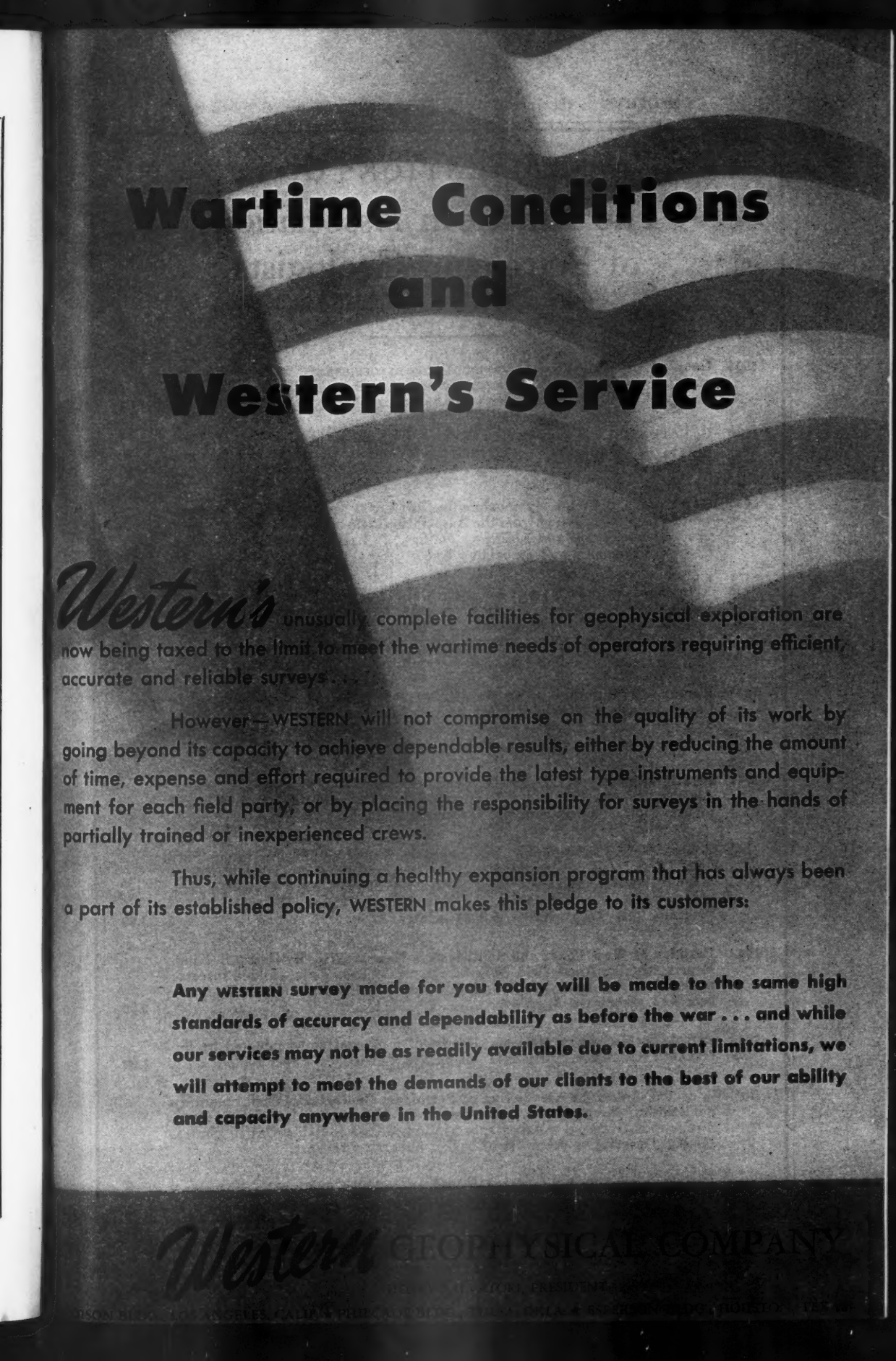

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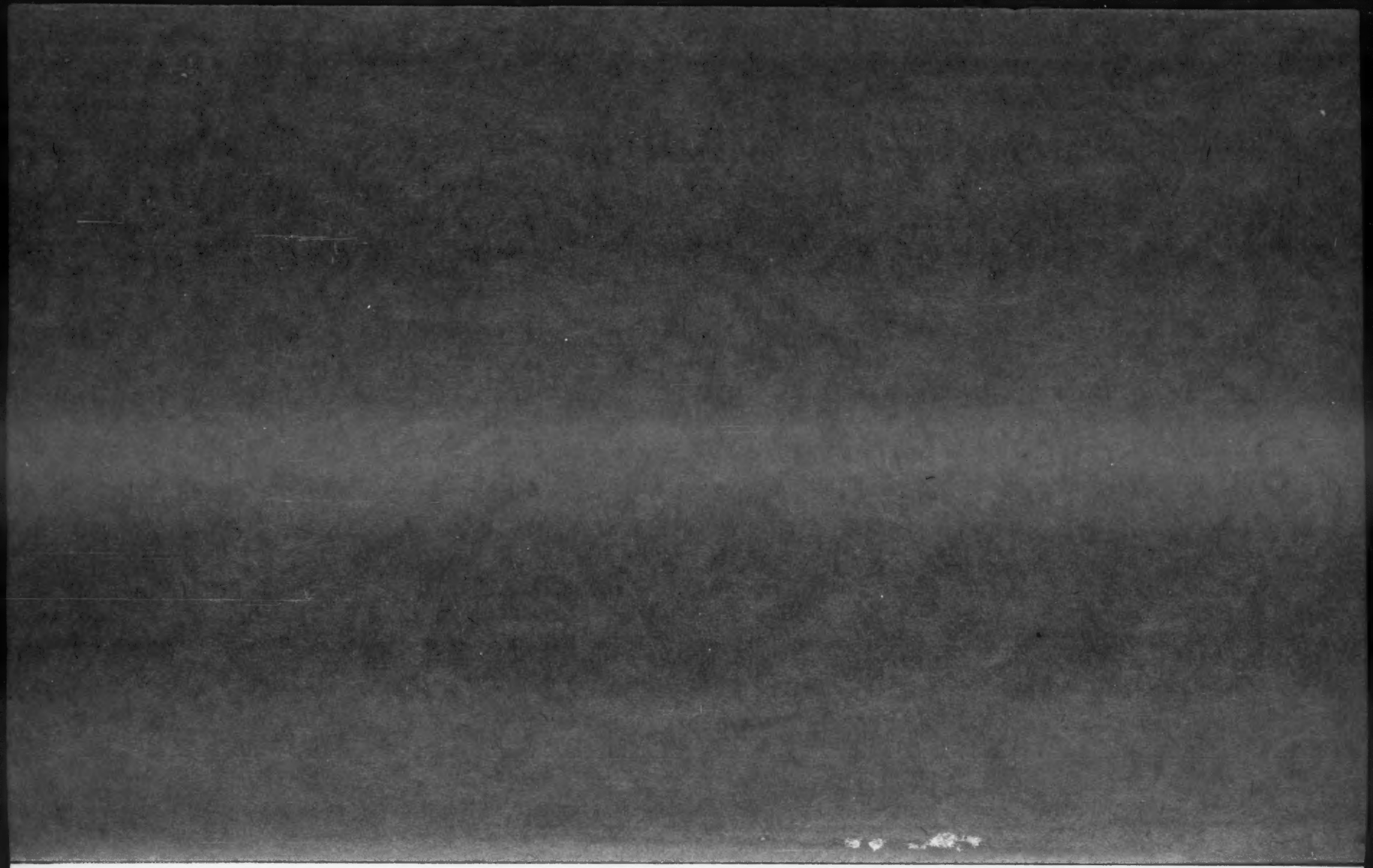
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